CNG AS A FEASIBLE REPLACEMENT FOR THE U.S. TRANSPORTATION SECTOR

THESIS

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Abstract

There has been much attention for many years on reducing U.S. fuel imports problem in order to improve energy independence. The transportation sector is one of the most important components with its share of 28% of total U.S. energy consumption. In this research, compressed natural gas (CNG) is examined to see if it can provide at least a partial solution to the problem of finding an alternative fuel for the U.S. transportation sector.

To be able to answer this question it is essential to understand both the supply and demand sides of the problem. This research aims to exhibit the availability and adequacy of CNG to be a full or partial fuel replacement for U.S. transportation sector needs, the factors that prevent CNG from being a widely used transportation fuel, the cost-benefit of using CNG as a vehicle fuel and feasible changes to make CNG more cost effective. In conjunction with putting forth this information for consideration, the short and long term best scenarios for CNG use in the transportation sector, provided through the application of Analytic Hierarchy Process (AHP), is proposed.

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Veysel Uz

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CNG AS A FEASIBLE REPLACEMENT FOR THE U.S. TRANSPORTATION

I. Introduction

In this chapter, a background of the study will be presented first, then the problem statement will be provided. Assumptions, limitations and the importance of the study will be explained.

Background of the Study

Natural Gas is one of the main sources used to satisfy total energy demand in the U.S. together with petroleum, coal, nuclear and renewable energies. The transportation sector captures a great portion of total energy consumption in the U.S.. Other important sectors in energy consumption are electric power generation, industrial, residential and commercial sectors.

The U.S., as one of the world's most industrialized countries, consumes 98 Q Btu (quadrillion British thermal units) per year (United States Department of Energy, 2010), nearly 18.7 % of world total energy consumption (United States Department of Energy, 2011). Natural gas covers 25% of this consumption. Only a small portion of natural gas (0.14%) is used for the transportation sector need as vehicle fuel while the majority of this source is used for residential and commercial (36%), industrial (30%) and the electricity generation sectors (34%) (United States Department of Energy, 2010).

The transportation sector is an important component of total energy consumption in the U.S. with its share of 28%. The dominating energy source in transportation is petroleum (93.2%), in the form of gasoline and diesel fuels. Other components are renewable energy (4%), natural gas (2.5%) and electricity (0.3%) (United States Department of Energy, 2010).

Finding efficient and inexpensive energy sources has been a major global challenge since the industrial revolution. In highly industrialized countries, like the U.S., with constantly growing energy demand, this issue has gained even more importance. Both because of competitive worries and energy independency considerations, reducing energy imports and standing on its own as much as possible emerges intrinsically as a tempting objective. With newly found natural gas reserves in the U.S., accomplishment of this objective could be easier than it was anticipated before.

World reserves of natural gas are immense with almost 72% of it concentrated around Middle East and Eurasia. Only Russia, Iran and Qatar account for 54.3%. More specifically, the world has 6842 Q Btu of natural gas reserves. The U.S. has proven natural gas reserves of 280 Q Btu (4.1% of world total) (United States Department of Energy, 2011) and projected recoverable reserves of 2155 quadrillion Btu (MIT, 2010) which cannot be easily neglected.

Domestic energy production in the U.S. is 75 Q Btu per year which corresponds to 76.5% of total annual energy consumption of the country. The country imports 30 Q Btu per year (30.6%) and exports 8 Q Btu per year (8.2%). Major part of imports is petroleum by 25.5 Q Btu per year. The remaining 4.5 Q Btu per year is other resources (natural gas, coal, coal coke, biofuels and electricity). The U.S. imports 49% of the petroleum it uses (United States Department of Energy, 2011). The largest portion of the petroleum is consumed as a transportation fuel at 71% (United States Department of Energy, 2010). In other words, the U.S. is 23.5% energy dependent in total. This dependency is mainly caused by petroleum imports at 85% of total transportation energy need. This means 14.2% of the country's energy dependency is a result of using petroleum powered vehicles as a means of transportation. Likewise the transportation sector is 46% energy dependent because of the same fuel preference.

Sustainability of shifting petroleum powered vehicles to vehicles that are powered by domestically produced fuels is an important matter. There is some research investigating the viability of natural gas as a transportation fuel. Yet, in order to deal with the viability of this option, its feasibility should be examined principally. Before initiating the accounting process of reviewing different strategies and computing possible consequences of this shift, the resource quantity, production, storage and transportation capacities ought to be checked. It can be said that feasibility paves the way for viability. To put it differently, there should be sufficient evidence of adequate supply to further investigate the demand side of the equation in terms of viability.

Problem Statement

The usage of natural gas as a transportation fuel is achieved through compressed natural gas (CNG) and liquefied natural gas (LNG). The reason to compress or liquefy natural gas is to create enough energy density to provide the vehicles a sensible range, since in its normal form natural gas does not contain enough energy to power a vehicle for acceptable distances.

In this thesis, compressed natural gas (CNG) is examined to see if it can provide at least a partial solution to the problem of finding a domestic alternative fuel for the U.S. transportation sector. Furthermore, four proposed scenarios are evaluated with respect to energy security and environmental impact, which are some of the main concerns of the U.S., for short-term and long-term with the purpose of developing an understanding of the benefits of different utilization of CNG as a transportation fuel. Therefore, the following research question is sought to be answered in this study.

- Is compressed natural gas (CNG) a feasible replacement fuel for the U.S. transportation sector?

To be able to answer this question it is essential to understand the supply side of the problem. Before investigating the viability of CNG as a replacement for gasoline and diesel fuel, the dominating fuels in the transportation sector, the question of its availability and its adequacy to be a full or partial fuel replacement for U.S. transportation sector needs to be answered. Adequacy of the U.S.'s natural gas reserves, production capacities of relevant firms, storage capabilities that facilitate overcoming disruptions in the demand and pipeline capacities to satisfy the seasonally fluctuating demand should be explained.

Next, the factors that prevent CNG from being a widely used transportation fuel should be examined. The cost-benefit of using a CNG vehicle will be calculated, and feasible changes to make CNG more cost effective will be examined. In conjunction with answering these questions, the short and long term best scenarios for CNG use in the transportation sector will be proposed.

To answer these primary questions, the research sub-questions in this study are:

- Based on the current and projected supply of natural gas in the U.S., how much of the U.S. transportation sector fuel requirement could 'possibly' be replaced by CNG? (Anecdotally – how much CNG would it take to replace all of the US transportation sector fuel requirement, and how long would it last?)

- Based on current U.S. infrastructure (and relatively low cost changes), how much of the U.S. transportation sector fuel requirement could 'feasibly' be replaced by CNG?
- What are the current barriers to CNG as a transportation fuel replacement? What is the cost-benefit (to the individual and nation) of using CNG power vehicles? What is needed to make CNG cost effective for the U.S. transportation sector, and what is the potential impact of that change?
- What are the possible and most feasible incremental changes (infrastructure, policy, or technology) that would make CNG more available or more cost effective for the US transportation sector?
- What is the best 'short-term scenario' for CNG use in the US transportation sector? What is the best 'long-term scenario' for CNG use in the US transportation sector?

Assumptions

The energy consumptions of scenarios are assumed to be constant over time as well as the end sector and total natural gas and energy consumptions. Consumption increases are not forecasted while making target achievement calculations. Likewise, natural gas production and storage capacities are assumed to be constant over time for the ease of calculations. The heating values for fuel types are taken as constant even though they change according to different geographical regions due to different climate conditions. The quantity of projected recoverable domestic natural gas reserves is taken from the report of the American Chemistry Council while there are several different predictions. LNG import options are ignored in calculations and assumed as insurance for the worst-case scenario in order to understand the domestic capabilities and to provide the conformance to the energy security policy. Target achievement values are assumed to be the relative importance assessments while calculating the priorities of the scenarios. Only four scenarios are selected for evaluation, whereas, there might be several scenarios for investigation.

Scope and Limitations

This study's scope is the U.S transportation sector and its possible benefits that could be gained from utilization of CNG as a vehicle fuel replacement. While conducting the analytic hierarchy process for the selection of the best short-term and long-term scenarios, only energy security and environmental impact objectives are taken into consideration. Other possible objectives, such as implementation costs for scenarios, are ignored.

Importance of the Study

Confirmation of CNG as a feasible replacement fuel for vehicles will contribute achieving some of the most important goals for the U.S. such as decreasing environmental impact and gaining energy security. In order to understand the importance of CNG as a transportation fuel, we will investigate the abundance of reserves, natural gas supply infrastructure and the benefits that could be gained from implementation. We will question the best scenarios for short-term and long-term using an analytic hierarchy process. The reader will be able to realize the impact of such a revolution. In the following chapter, a literature review will be provided for the purpose of explaining the need for this study.

II. Literature Review

Natural gas is a clean and domestic energy source for the U.S. Even though it is a fossil fuel like petroleum and coal, it can be identified as much more environmental friendly. Besides, domestic reserves are encouraging to consider its more widespread utilization. A significant amount of energy requirement of the country is satisfied by natural gas at about 25%. It is surprising to see the transportation sector seems to be far away from taking advantage of natural gas while other end use sectors like industrial, commercial, residential and electricity generation sectors are using it as one of their prime energy sources. That may be the result of the anticipated on board fuel storage space drawback. The main problem of natural gas in its natural form is its low energy density. With the same amount of volume of fuel it gives less energy than conventional fuels such as gasoline or diesel. The main idea behind compressing the natural gas is to make it provide sufficient energy to be able to be used in daily operations. Compressed natural gas is a dense form of the natural gas in less than 1/100th of its volume at standard atmospheric pressure and temperature. In this form, it could give more energy to be considered as a candidate for a transportation sector replacement fuel.

The purpose of this literature review is to indicate the need for this study via improving the understanding of importance, advantages and superiorities as well as the limitations of using natural gas for the U.S. and compressed natural gas as a fuel for the U.S. transportation sector.

Natural Gas

Natural gas is a fossil fuel in a gaseous form which is dominantly composed of methane and other hydrocarbons. Natural gas may contain 85 percent methane (CH_4) and about 10 percent ethane (C_2H_6), and also contains smaller amounts of propane (C_3H_8), butane (C_4H_{10}), pentane (C_5H_{12}), and other alkenes (Lumato, 2005). Although natural gas (NG) which is a colorless, odorless and tasteless fossil fuel, is a non renewable energy resource like other fossil fuels such as petroleum derivatives and coal, and uranium (nuclear energy), it is characterized as one of the cleanest and safest energy sources worldwide. (Borraz-Sanchez, 2010).

Natural gas is a combustible mixture of gases which contain carbon and hydrogen. The composition of natural gas can change; in figure 1 general components of natural gas before refinement process is listed.

Methane	CH_4	70-90%
Ethane	C_2H_6	
Propane	C_3H_8	0-20%
Butane	C_4H_{10}	
Carbon Dioxide	CO_2	0-8%
Oxygen	O_2	0-0.2%
Nitrogen	N_2	0-5%
Hydrogen sulfide	H_2S	0-5%
Rare gases	A, He, Ne, Xe	trace

Figure 1 Typical Composition of Natural Gas

(www.NaturalGas.org)

On the other side, natural gas contains small amounts of impurities, including carbon dioxide (CO_2), hydrogen sulfide (H_2S), and nitrogen (N_2). These impurities can decrease the heating value and properties of natural gas. In order to make natural gas efficient and cleaner burning, it needs to go through a refining process. During the refining process the impurities are removed and used as commercial by-products (Lumato, 2005). In figure 2, the refining process is shown. Depending on the source and type of gas stream, if the gas is together with oil in the source and it is not naturally separated from it, gas-oil separators may be necessary. In the condensate separation process, free water is separated from natural gas before the dehydration process in which the removal of water captured in the form of hydrates takes place. After removal of contaminants like hydrogen sulfide, carbon dioxide, helium and oxygen cryogenic nitrogen extraction process begins. In the penultimate step methane separation is conducted and in the last step natural gas liquids such as ethane, propane, butane and pentane are fractioned by boiling.

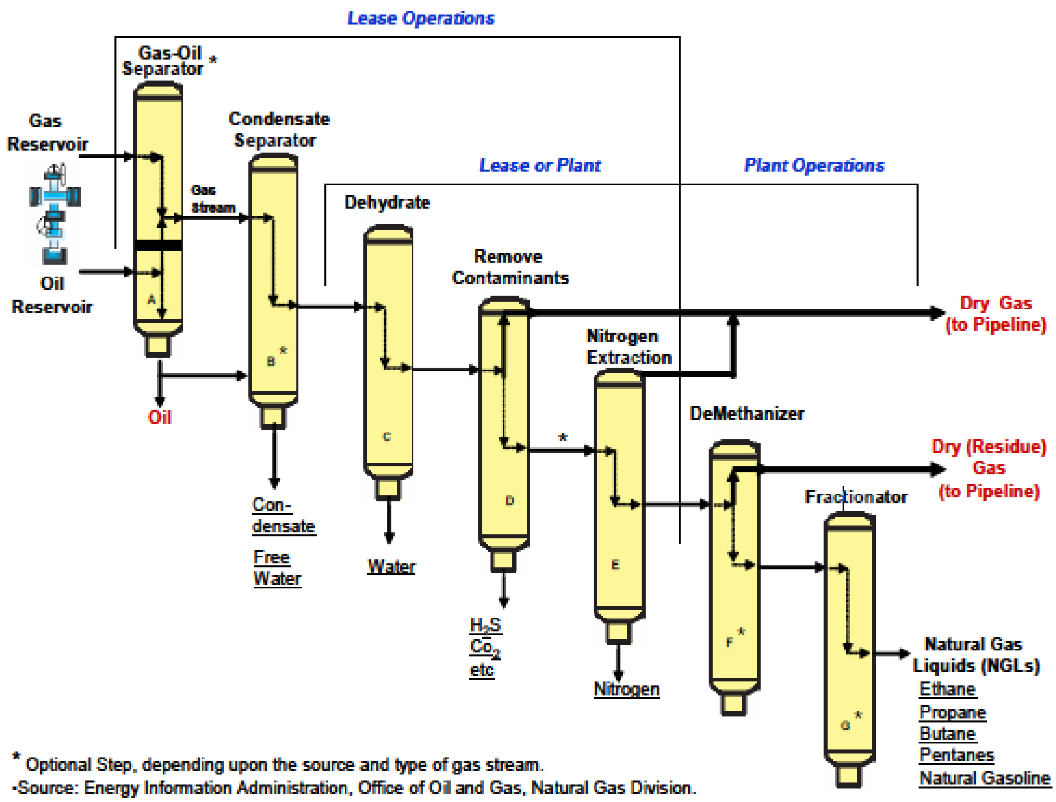

Figure 2 Natural Gas Refining Process

(Energy Information Administration, 2006)

The formation of natural gas is not so different than oil's. It is formed from dead marine organisms. Millions of years ago, organic matter from these organisms collected on ocean floors and was covered by sediments before full decomposition. Over time, heat and pressure of successive layers of sedimentation broke down this organic matter into simpler and simpler hydrocarbon chains. The longer chains are liquid at standard temperature and pressure and comprise the range of petroleum products—oil, waxes, etc. The shortest hydrocarbon chains are gaseous at standard temperature and pressure and make up natural gas (McElroy, 2010).

Human realization of natural gas as a utilizable resource goes back to comparatively recent dates. Mokhatab et al. mention that the Chinese drilled the first known NG well in 211 B.C. A few centuries later, they would employ crude bamboos as a means to transport NG (Mokhatab, 2006). In North America, in 1816, the Americans began using NG for lighting the streets of Baltimore, Maryland. A few years later, in 1821, William A. Hart would be the first one to succeed in digging a 27ft wellhead in Fredonia, New York, USA (Speight, 1993). After many cities had begun replacing their gas lamps with electric lamps, expansion of natural gas usage had to slow down until the end of World War II, the time the technological progress in pipeline manufacturing, metallurgy and welding was achieved (Borraz-Sanchez, 2010). It can be seen from figure 3 that, in a quarter century since then the consumption of natural gas in the U.S. was quadrupled. Still there should be more space for natural gas in the market. In figure 3, we could also see that NG usage by the transportation sector is well below other sectors. If it had overall bad characteristics as a fuel, it shouldn't have been utilized this much. Since other end use sectors use it widely, natural gas should have some advantages. This may be the time for transportation sector to enjoy those advantages. In the following paragraphs, some of these advantages will be addressed.

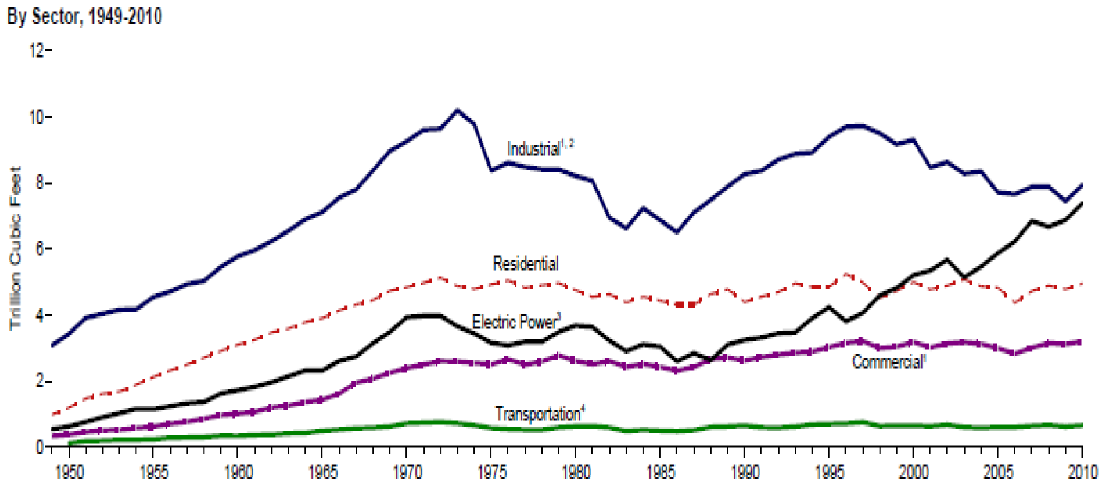

Figure 3 U.S. Natural Gas Consumption by End Use

(Energy Information Administration, 2010)

Natural gas has superior cleanliness features. Among the fossil fuels, it has the lowest carbon intensity, emitting less carbon dioxide per unit of energy generated than other fossil fuels. It burns cleanly and efficiently, with very few non-carbon emissions (MIT, 2010). Although its combustion does produce greenhouse gases, it is a more environmentally clean alternative to petroleum fuels, and it is much safer than other fuels in the event of a spill (Alias, 2008). NG produces lower levels of CO_2, CO, water vapor and particulate matter than other fossil fuels. Figure 4 shows the fossil fuel emission levels provided by U.S. Energy Information Administration (EIA) in pounds of pollutants per B (Billion) Btu of energy input of fossil fuels (United States Department of Energy, 1999).

	Fossil fuels (pounds per Billion Btu of energy input)		
Contaminant	Natural gas	Oil	Coal
CO_2	117,000	164,000	208,000
CO	40	33	208
NO_x	92	448	457
SO_2	1	1,122	2,591
Particulates	7	84	2,744
Mercury	0.0	0.007	0.016

Figure 4 Fossil fuel emission levels

(United States Department of Energy, 1999)

Natural gas generally requires limited processing to prepare it for end-use, compared to oil (MIT, 2010). Natural gas processing plants, also called fractionators, are used to remove the impurities or contaminants, such as CO_2, H_2O, H_2S, He, mercury and nitrogen found in the raw natural gas as mentioned above. After fractioning is completed natural gas liquids, which are also put separately in the market as valuable by-products, include ethane, propane, butane and pentane, are obtained as well (Borraz-Sanchez, 2010).

One other good property of natural gas is its high recoverability in conventional reservoirs at lower costs due to its high compressibility and low viscosity characteristics. Also as proven in shale operations, natural gas can be economically recovered from even the most unfavorable subsurface environments (MIT, 2010). While oil reservoirs naturally produce 10% to 30% of the oil found, natural gas reservoirs generally produce 70% to 80% since it is in a gaseous form. Because of its compressibility feature more gas can be stored in reservoirs than oil (Hefner, 2009). As a result of development in technology which makes shales accessible, the level of reserves has been updated to be significantly higher. Current U.S. natural gas flow including the contribution of shale gas production can be seen in figure 5. Another positive development about natural gas is new fractionators. Although new generation natural gas processing plants are smaller in capacity they have the advantage of mobility which mitigates the worries about high infrastructure investment costs.

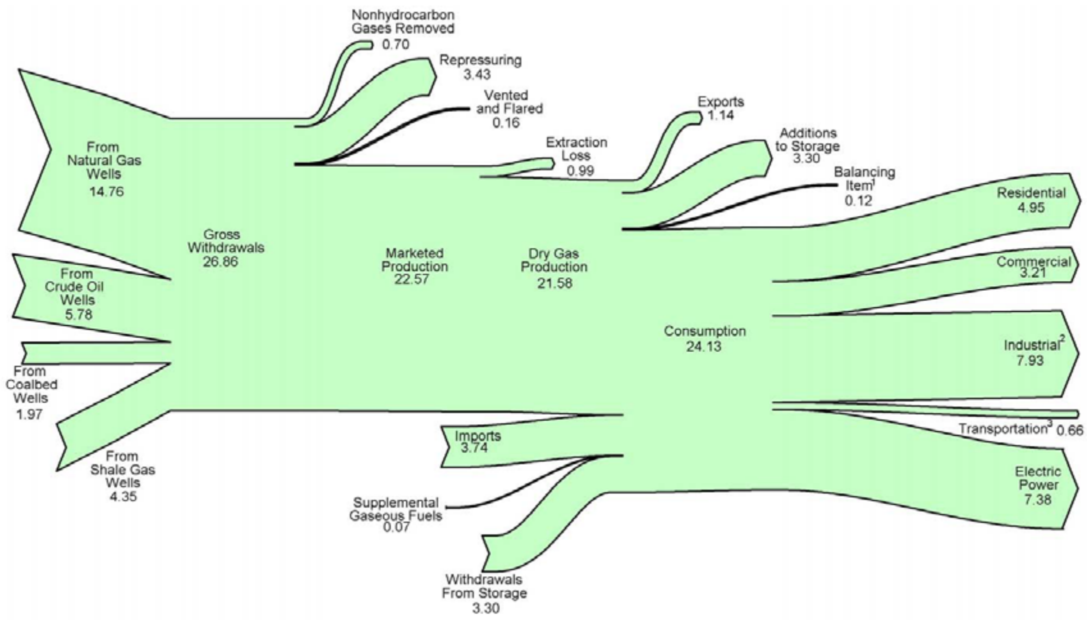

Figure 5 Natural Gas Flow

2010 (Tcf), (Energy Information Administration, 2011)

These positive features of natural gas make it a favorable fuel for different sectors. According to EIA, shown in figure 6, 33.84% of the U.S. natural gas is consumed for electric generation. Industrial consumption's share is 29.86% while 21.95% is used for residential need and 14.21% is used for commercial purposes. It is interesting and worthy of investigation that only 0.14% of total natural gas consumed is used as vehicle fuel while the U.S. currently satisfies nearly 25% of its total energy requirement from this major and advantageous resource.

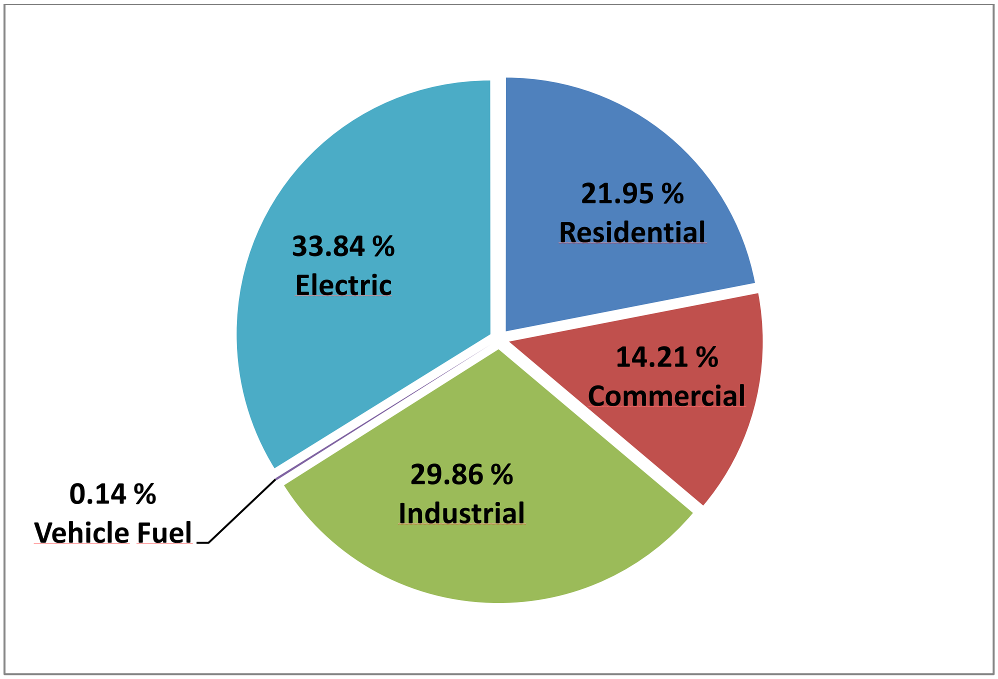

Figure 6 Natural Gas Consumption by End Use

(Energy Information Administration, 2011)

CNG as a Transportation Fuel

Under normal conditions, natural gas does not possess enough energy density to provide a satisfactory range as gasoline or diesel vehicles when used as a transportation fuel. It is for sure not convenient for drivers either to have gigantic fuel tanks on vehicles or to stop several times for refueling even in a short distance travel. In order to overcome this problem while using natural gas as transportation fuel effectively there are currently two main suggested solutions. One of them is liquefying the natural gas by cooling it to cryogenic temperatures (-260F) to assure it is keeping less space. Liquefied natural gas is abbreviated as LNG and it takes up about 1/600th the volume of natural gas in the gaseous state. The tradeoff between having the advantage of storing natural gas in a liquid form and the endeavor to keep it cryogenically cold is a matter of debate. The other solution to fit the gas in a reasonable size tank, is compressing it. The focus material of this study, compressed natural gas (CNG) is made by compressing natural gas to less than 1/100th of its volume at standard atmospheric pressure and temperature. It is stored and distributed in hard containers, at a normal pressure of 200–220 bar (2900–3200 psi), usually in cylindrical or spherical shapes.

The vehicles powered by compressed natural gas need greater gas tank space than gasoline or diesel powered vehicles. Since it is a gas even though it is compressed, rather than a liquid like gasoline, CNG takes up more space for each Gallon of Gas Equivalent (GGE). CNG has approximately 25% of the energy density of gasoline (Murphy, 2010). Therefore, the tanks used to store the CNG usually take up additional space in the trunk of a car or bed of a pickup truck which runs on CNG (Alias, 2008). It also requires special storing capability. CNG is stored in a steel or carbon fiber tank at approximately 200 atmospheres.

Besides the vehicles marketed by original equipment manufacturers, the conversion of the ordinary vehicles is also possible. Compressed natural gas can be used in any four-stroke (gasoline) and modified Diesel cycle engines. The equipment required for CNG to be delivered to a four-stroke engine includes a pressure regulator (a device that converts the natural gas from storage pressure to metering pressure) and a gas mixer or gas injectors (fuel metering devices). Often assisting the gas mixer is a metering valve actuated by a stepper motor relying on feedback from an exhaust gas oxygen sensor. Newer CNG conversion kits feature electronic multi-point gas injection, similar to petrol injection systems found in most of today's cars (Alias, 2008). Easy conversion of current vehicles to CNG could make it appealing for various transportation applications such as daily use for residentially owned light vehicles or heavy vehicles such as commercial trucks, water vessels and trains or governmental vehicles like buses, and street sweepers.

The demand for transportation fuel in the U.S. shows a positive trend. It increased on an average of 2.5% per year over the last 40 years as it can be seen from figure 7. This requirement is dominantly satisfied by gasoline and diesel. In 2010, the U.S. transportation sector fuel requirement was 27,506,882 B Btu. In other words, 26.836 Tcf (Trillion cubic feet) of natural gas would be required to replace all transportation sector fuel requirements for a year since one cubic foot of natural gas is equal to 1025 Btu based on the calculations of U.S. consumption of 2010 (United States Department of Energy, 2010). Satisfying this rapidly increasing demand as much as possible with domestically produced fuels with lower environmental impact rather than imported petroleum fuels with high cost and pollution effect emerges as a more logical choice with respect to energy independency and environmental concerns.

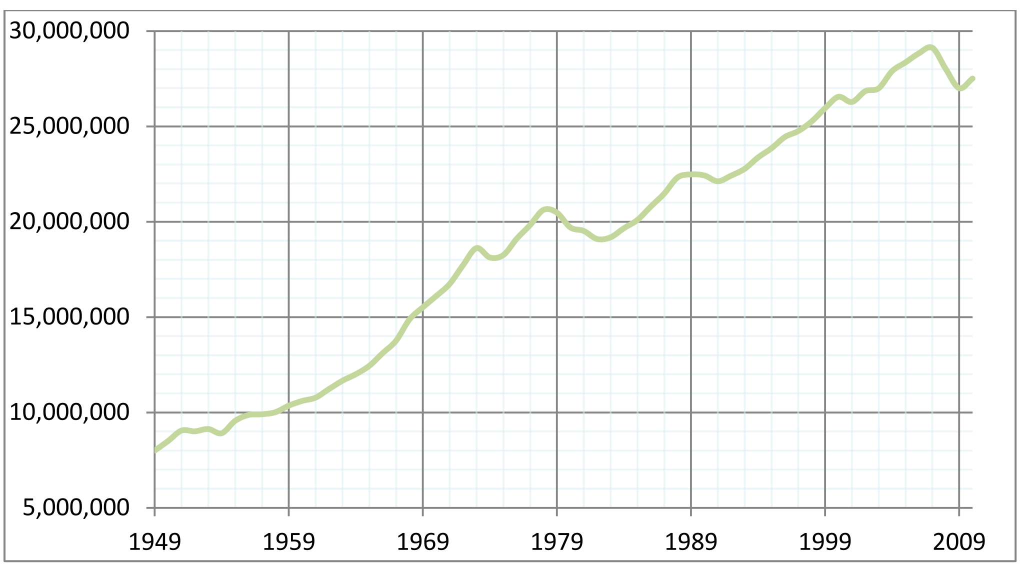

Figure 7 U.S. Transportation Sector Fuel Consumption

(Billion BTU), (Energy Information Administration, 2011)

Reserves

The U.S. natural gas reserves are proven to be abundant with the development of shale technology. The United States has predicted reserves of 2,552 Tcf, 32% of which is shale gas (827 Tcf) that was thought to be unrecoverable up until recently (American Chemistry Council, 2011). This addition to natural gas reserves has changed the attitude towards the utilization opportunities of this resource. Total US natural gas resources are estimated to be large enough to supply over 100 years of demand under current production rates. According to the growth of domestic recoverable reserves, production and transportation capacity has begun increasing sharply and a considerable amount of decrease in pipeline and LNG imports was experienced.

The transportation sector which uses only a small amount of these abundant reserves and capacity could be considered as a new natural gas market for the reason of currently being highly dependent to foreign petroleum products. As mentioned before the transportation sector is 46% energy dependent due to wide usage of petroleum. Also the sector's share of total CO_2 emissions is about 32% (Energy Information Administration, 2011). The successful transformation of the transportation sector to use domestic natural gas is going to have a significant impact on energy independency of the country as well as the environmental bad reputation of the sector.

Infrastructure

Natural gas infrastructure is composed of production facilities, LNG import terminals, pipelines and refueling stations. The life cycle of natural gas starts with the production and ends at end user. After natural gas is extracted from underground it is sent to natural gas processing plants for purification. Then natural gas is pumped into pipelines to be sent to demand areas. There, it is served to end users, such as refueling stations for vehicles, power plants or industrial facilities. LNG import terminals are equipped to regasify the liquefied natural gas that is brought by LNG ships in cryogenic temperatures. A general scheme of natural gas infrastructure can be seen in figure 8. Natural gas infrastructure components will be examined in the following sections.

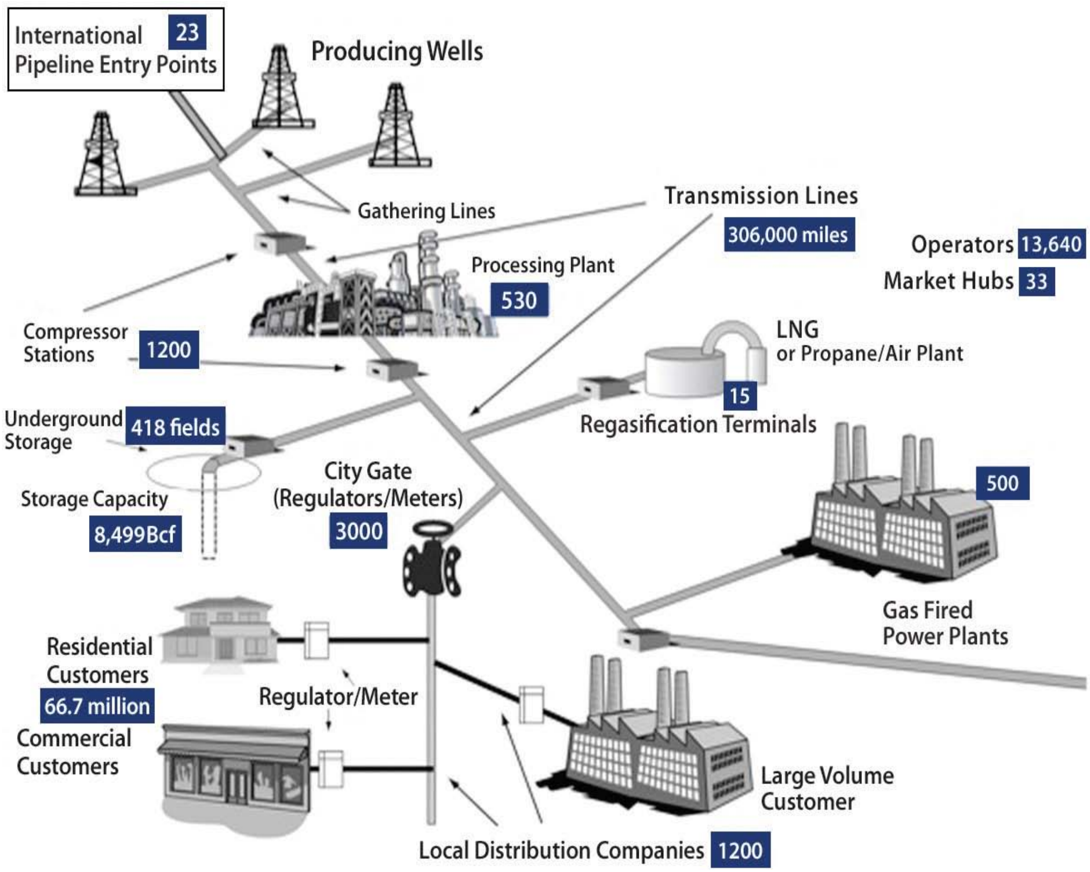

Figure 8 Natural Gas Infrastructure

(MIT, 2010)

Production

Production of natural gas is achieved through three phases. In the beginning, reserves that are economically valuable for drilling must be found via advanced techniques like seismic exploration, then using vertical or horizontal drilling techniques natural gas is extracted. Finally to purify and prepare it for transportation to demand areas, as explained in chapter 2.1, natural gas is processed in natural gas processing plants (fractionators). All production procedures must be organized in order to meet the required qualifications that are dictated by the Natural Gas Act of 1938, the Natural Gas Policy Act of 1978, the Outer Continental Shelf Lands Act, the Natural Gas Wellhead Decontrol Act of 1989, and the Energy Policy Act of 1992 and controlled by Federal Energy Regulatory Commission (FERC).

The most important factor is the production capacity since the development of drilling technologies has allowed abundant reserves to be recoverable once thought to be unrecoverable. As it can be seen from Figure 9, the country has a daily production capacity of 90.8 Bcf (Billion cubic feet), as of 2010. Natural gas processing capacity in the U.S. is growing rapidly. Between 2009 and 2010 13.3 Bcfd (Billion cubic feet per day) capacity was added to an existing 77.5 Bcfd (U.S. Energy Information Administration, 2011).

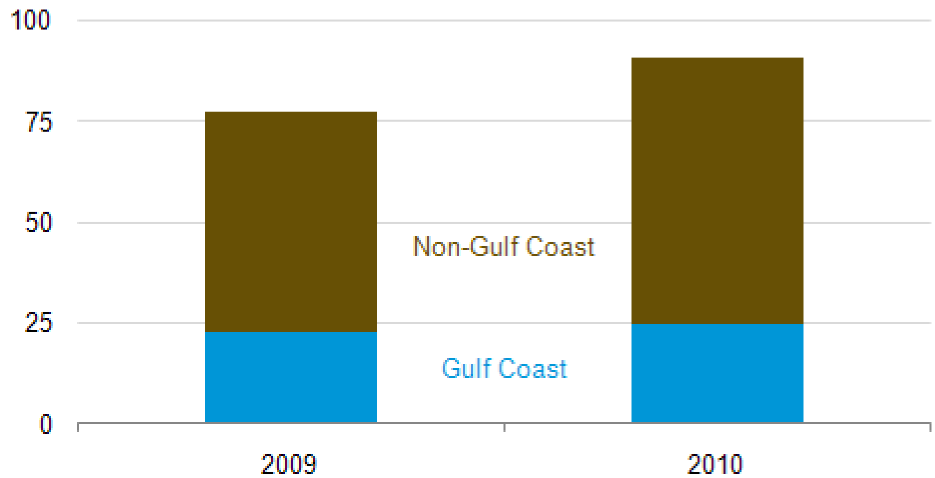

Figure 9 U.S. Natural Gas Processing Plant Capacity

(Bcfd), (U.S. Energy Information Administration, 2011)

Since the processing capacity emerges as a bottleneck in the production process, the major development has concentrated on increasing it. An important factor taken into consideration in building new processing plants seems to be their mobility. The new mobile plants allow the producers to relocate them as needed when the newly reachable more widespread reserves happen to deplete. In Figure 10, locations of existing U.S. natural gas processing plants as of 2010 can be seen.

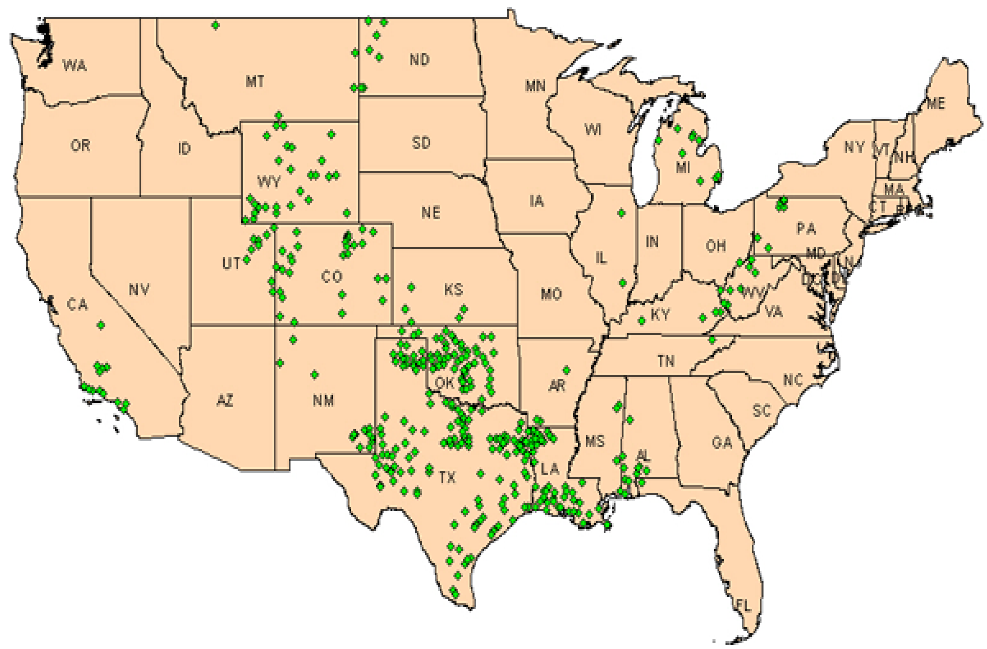

Figure 10 Existing U.S. Natural Gas Processing Plants

(Fessler, 2011)

The total U.S. natural gas production was 22.12 Q Btu in 2010 where current annual total capacity is 33.97 Q Btu (Energy Information Administration, 2011). This shows a capacity utilization of 65.12%. Roughly speaking, there's more than 1/3 unused production capacity in 2010 which can be directed for use in the transportation sector, as well as other end use sectors. On the other hand 10.9% of consumed natural gas in the U.S. in 2010, Figures 11 and 12, was imported from Canada mainly, but also Trinidad and Tobago, and other countries. A trade overview of natural gas over the years can be seen in figure 13. Satisfaction of increasing natural gas demand could be maintained with domestic supply by eliminating the bottlenecks like production capacity and implementing effective policies like the efficient utilization of natural gas as a vehicle fuel. Another consideration about making use of natural gas is its transportation capacity. In the next section the means of transportation for natural gas will be discussed.

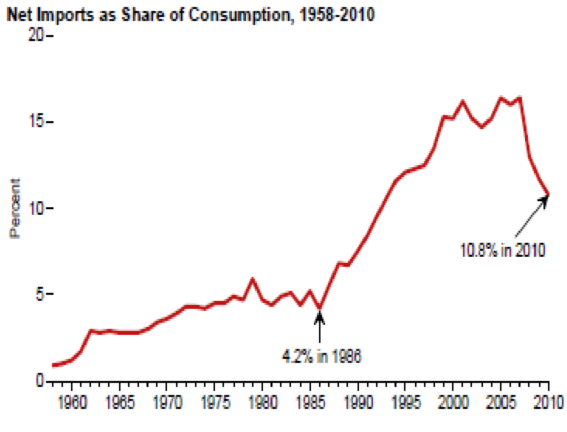

Figure 11 Net Imports as Share of Consumption

(Energy Information Administration, 2011)

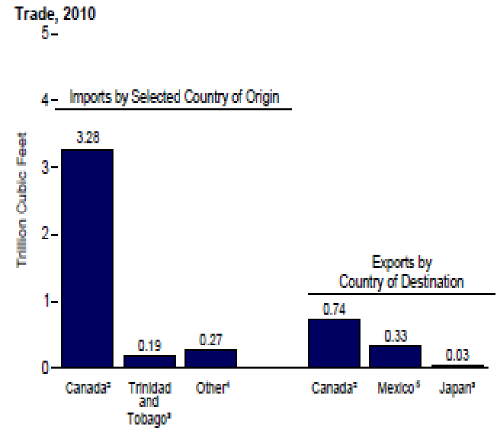

Figure 12 Imports by Country of Origin

(Energy Information Administration, 2011)

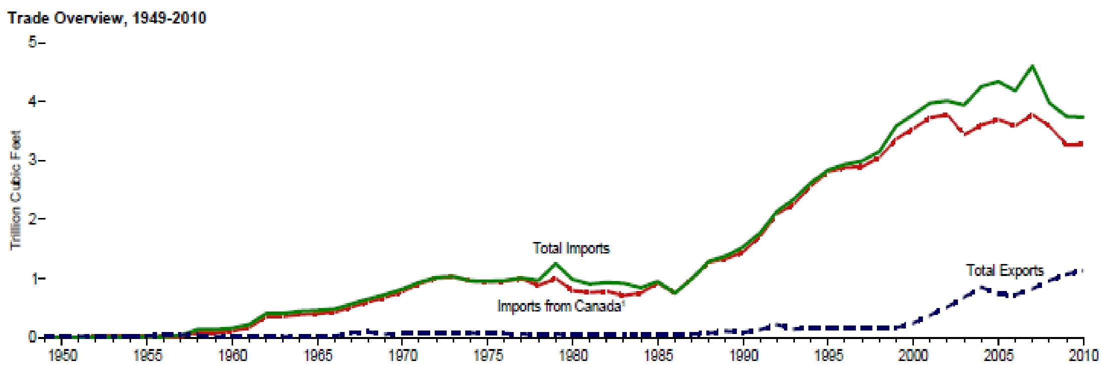

Figure 13 Natural Gas Trade Overview over the Years

(Energy Information Administration, 2011)

Transportation

Transportation and distribution of natural gas is provided through LNG ships and pipelines. LNG has been used as a supplementary source especially in peak demand times like winters because of the insufficient natural gas production capacity. LNG imports to the U.S. could be expected to drop proportional to the increase of production capacity. The U.S. has a total of 18.84 Bcfd LNG import capacity as of 2012 through its 12 import terminals. The main means of natural gas transportation is pipeline infrastructure. The importance given to the pipelines as the sole means of domestic natural gas transportation is increasing. This is because of the federal energy security policies such as the Energy Security Act of 2011 which projects to terminate energy imports from outside North America by the year 2030. The U.S. daily pipeline capacity has reached 255.13 Bcf as of 2011 with significant additions over the last 5 years in parallel to this. In the following sections two means of natural gas transportation, LNG imports and pipelines, will be explained.

LNG Imports

In times of insufficient supply to meet demand, such as winter months when natural gas production falls behind the requirement, or production has interruptions such as the during hurricanes like Rita and Katrina, supply has been supported by LNG imports. LNG ships are used to import LNG. Natural gas is liquefied by cooling it to cryogenic temperatures (-260 F) at the exporter country terminals, it is carried by cryogenic LNG ships and it is regasified at the importer country's terminal before putting it into pipelines. U.S. LNG import terminals have played an insurance role so far. It could be important to keep this insurance in the drawer, but in the abundance of this resource's domestic reserves, using that option as often as it has been so far should not be necessary with respect to energy independency. The U.S. has a total LNG import capacity of 18.84 Bcfd (19.31 T Btud) as of 2012 through its 12 import terminals as it is seen in Figure 14 (Federal Energy Regulatory Commision, 2012) In 2010, LNG imports accounted for 11% of total natural gas imports and 1.81% of total annual natural gas consumption, Figure 15. In accordance with the purpose of this study, LNG imports will not be taken into consideration while making calculations.

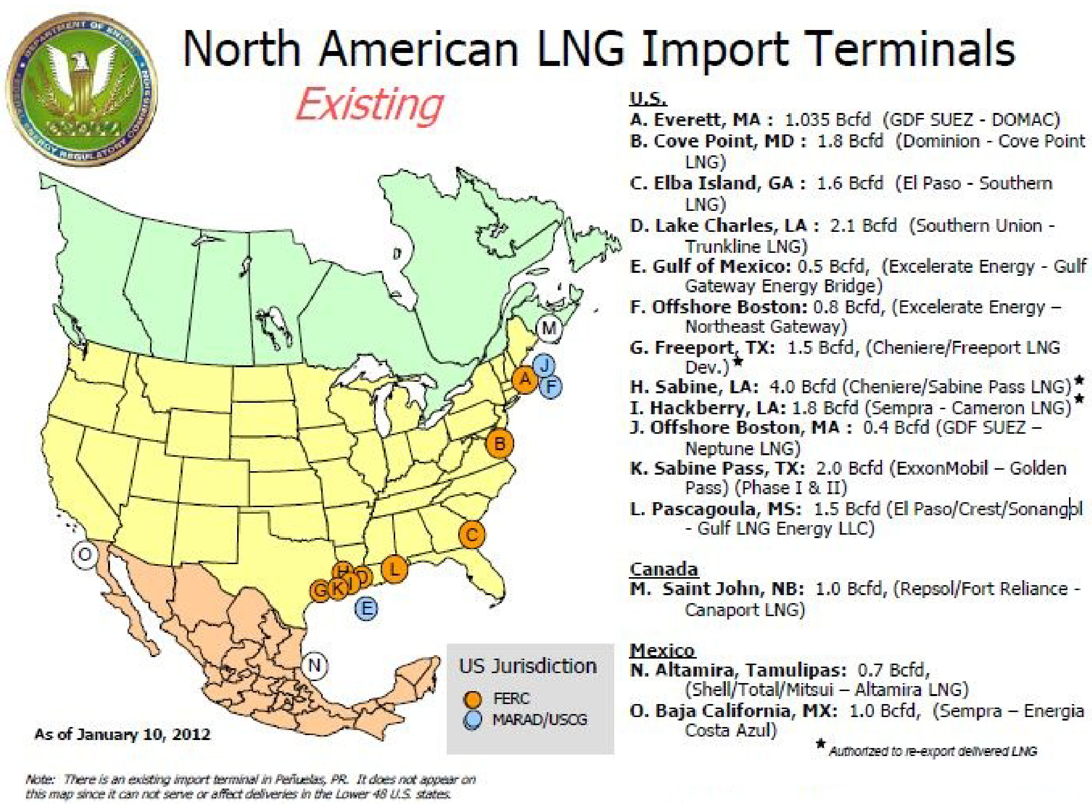

Figure 14 North American LNG Import Terminals

(Federal Energy Regulatory Commision, 2012)

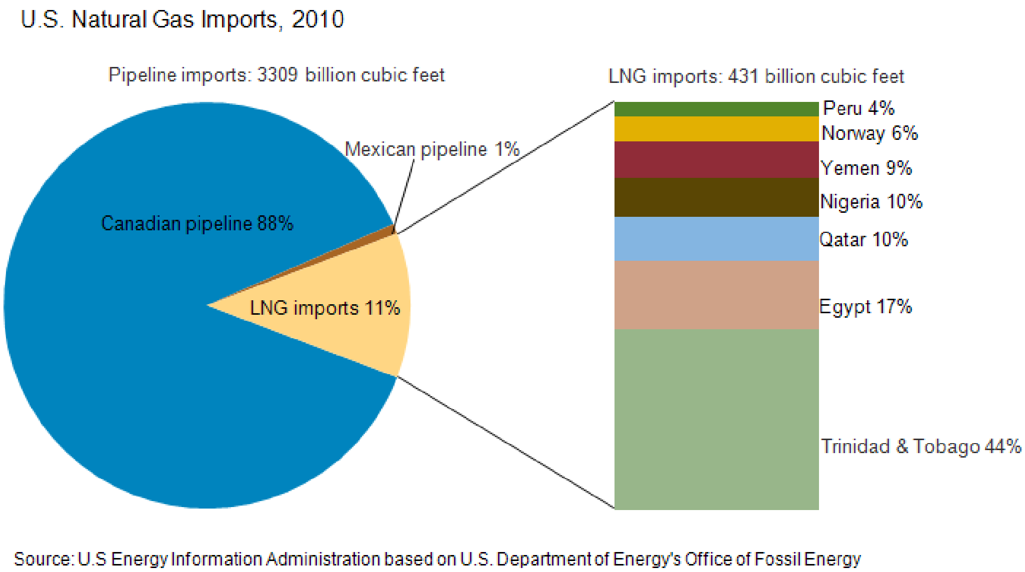

Figure 15 U.S. Natural Gas Imports

(United States Department of Energy, 2010)

Pipelines

Pipelines are the main corridors to transport and distribute natural gas. On average, 67 Bcf of natural gas is transported daily in the U.S. where pipeline capacity is 255.13 Bcfd as of 2011 with significant additions of nearly 115 Bcfd over the last 5 years, as it is seen in Figure 16 (Energy Information Administration, 2012; Energy Information Administration, 2008; MIT, 2010). The U.S. pipeline infrastructure can be seen in Figure 17. Overall pipeline capacity of 255.13 Bcfd does not appear as a constraint, where production capacity is still 90.8 Bcfd by 2010, while meeting the increasing natural gas demand. Moreover, the pipeline utilization rate of 73.74% on an annual basis in 2011 supports this idea. However the pipeline capacity usage should not be determined based on annual utilization average. The utilization could be low in periods of low demand like summer months and could be seen as sufficient but in times of high demand some pipelines' utilization might be higher than 100% by way of exceeding certified limits. It is not a dangerous thing to do over a short period time because of the high safety design specifications.

Pipeline design, construction, operating and maintenance are regularized by The U.S. Department of Transportation's standards that are stated in 49 CFR Part 192—"Transportation of Natural Gas and Other Gas By Pipeline: Minimum Safety Standards" (Government Printing Office). Federal Energy Regulatory Commission (FERC) is in charge of controlling pipelines obtaining authorization from the Natural Gas Act of 1938, the Natural Gas Policy Act of 1978, the Outer Continental Shelf Lands Act, the Natural Gas Wellhead Decontrol Act of 1989, and the Energy Policy Act of 1992. FERC certified capacity represents a minimum level of service that can be maintained over an extended period of time, and not the maximum throughput capability of a system or segment on any given day (Energy Information Administration). So it is possible to use additional compression to increase throughput temporarily, within safety limits. The bottom-line is, in spite of over capacity utilization of pipelines for transportation of natural gas in peak demand periods, the U.S. had to import natural gas with LNG ships. With recent additions to production capacity, any more additions to production capacity do not seem to be as necessary as before with respect to current production and consumption quantities. As a result, current U.S. pipeline capacity, together with the continued capacity growth rate could allow transporting very large amounts of natural gas, proving itself as a non-bottleneck.

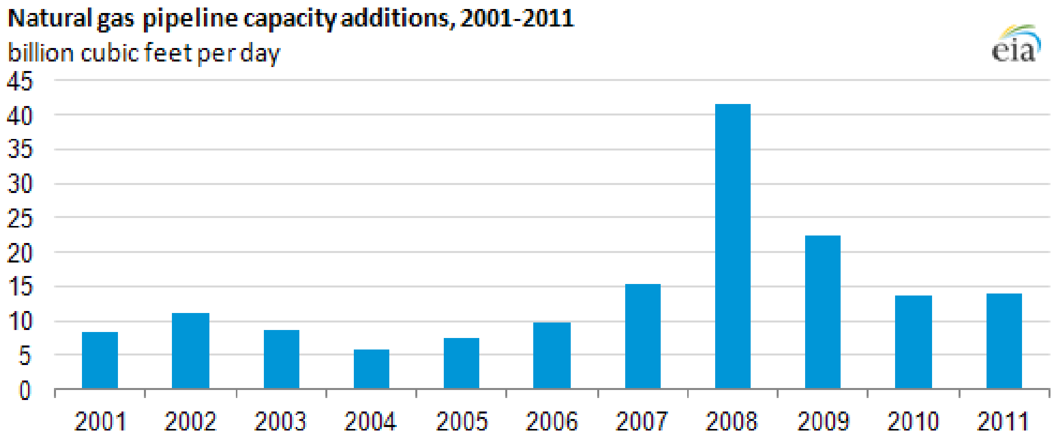

Figure 16 Natural Gas Pipeline Capacity Additions

(Energy Information Administration, 2012)

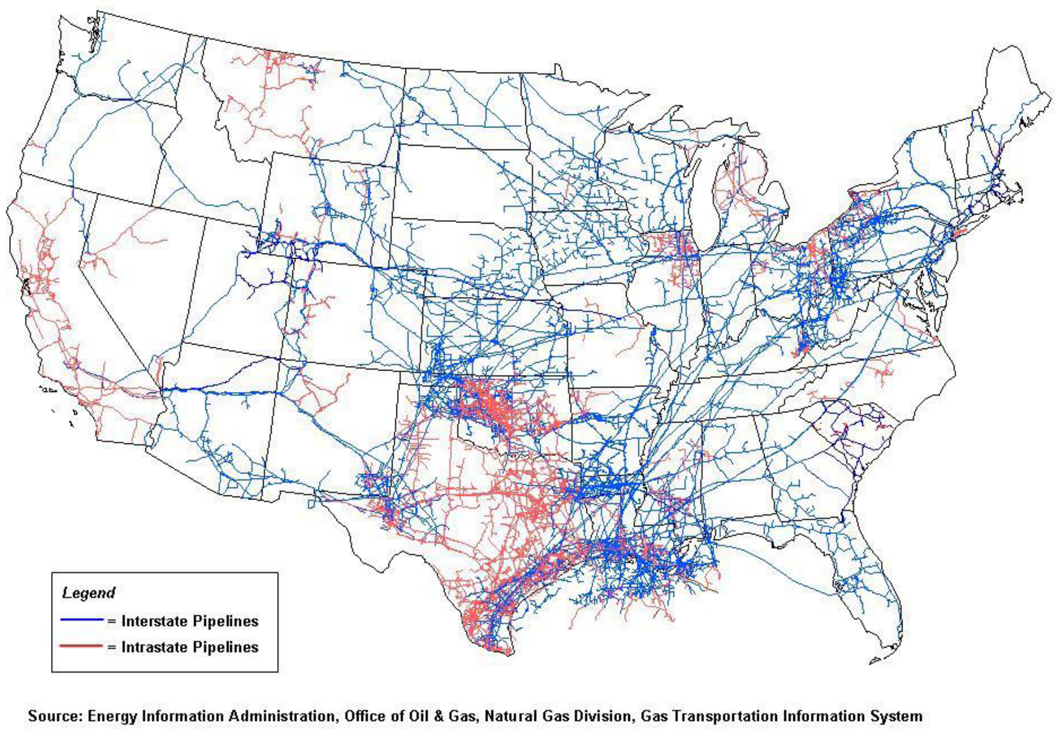

Figure 17 U.S. Pipeline Infrastructure

(Energy Information Administration, 2011)

Refueling

In the U.S. there are a total of 975 CNG and 46 LNG refueling stations as of 2012, a very small percentage compared to the number of petroleum refueling stations (U.S. Department of Energy, 2012). Most of them are privately owned and are used for central refueling. They are not distributed evenly around the country. On the other hand, home refueling may be an option. Individual vehicle users may refill their CNG vehicles using a residential CNG refueling station, like the one that was made by Honda. The main disadvantage of this option is that the vehicle must be in a small radius around the house and is not convenient for longer trips due to limited ranges provided by current on-board fuel storage capacity. Besides, it takes great amount of time like 16 hours to fill a natural gas cylinder, since a fast filling option for home refueling has not been developed yet. Overall, refueling infrastructure is an area that requires investment. Unless there is a solution for increasing the range of CNG powered vehicles and providing a widespread refueling infrastructure, refueling is bound to be an important limitation for CNG use for transportation.

III. Methodology

Introduction

It has always been a challenge for people to make decisions since it is not possible all the time to decide based on precise mathematical computations. Therefore, developing decision making methods has been an important need for practitioners and a great point of interest for scholars. Correspondingly, decision making literature is enormous. But developing the best decision making method for particular real life phenomenon is still a challenging struggle. Multi-criteria decision making (MCDM) is one of the most popular fields of study of decision making. There are some common notions in different MCDM methods which are called alternatives and attributes (also called goals or decision criteria) (Triantaphyllou, 2000).

- Alternatives: Different courses of action available to the decision maker, which can be infinite theoretically but assumed to be finite and generally few for the ease of operation. There may be a great number of houses available for sale, but only a few are thought to be candidates for further evaluation for buying. Alternatives are supposed to be screened, prioritized and ranked.
- Multiple Attributes: MCDM problems have multiple decision criteria. Each of the multiple attributes represents a different point of view from which the alternatives can be assessed. A hotel may be evaluated by its cleanliness, service quality and location.

- Conflict among Criteria: There may be conflicts among each goal because they represent different perspectives of the alternatives. For example, for a person who will purchase a car, desired engine size and price of a car may conflict.
- Incommensurable Units: Different decision criteria may be measured by different units of measure such as dollars for profit and feet for depth. In general, this complexity is an important factor making MCDM problems hard to solve.
- Decision Weights: Decision criteria need to be weighted according to their relative importance to each other in most of the MCDM methods. Taste of a meal at a restaurant may be more important than the price of it for a person.
- Decision Matrix: An MCDM problem could be expressed in a matrix format. A decision matrix A is an (m x n) matrix in which element a_{ij} indicates the performance of alternative A_i when it is evaluated in terms of decision criterion C_j (for i = 1, 2, 3, …, m, and j = 1, 2, 3, …, n). Zimmerman defines and shows decision matrix (figure 18) as follows (Zimmermann, 1991):

Let $A = \{ A_i$, for $i = 1,2,3,\ldots ,M\}$ be a (finite) set of decision alternatives and $G = \{g_i$, for $j = 1,2,3,\ldots, N\}$ a (finite)set of goals according to which the desirability of an action is judged. Determine the optimal alternative A^* with the highest degree of desirability with respect to all relevant goals g_i.

	Criteria				
	C_1	C_2	C_3	...	C_N
Alternatives	W_1	W_2	W_3	...	W_N
A_1	a_{11}	a_{12}	a_{13}	...	a_{1N}
A_2	a_{21}	a_{22}	a_{23}	...	a_{2N}
A_3	a_{31}	a_{32}	a_{33}	...	a_{3N}
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
A_M	a_{M1}	a_{M2}	a_{M3}	...	a_{MN}

Figure 18 A Typical Decision Matrix

(Zimmermann, 1991)

Most commonly used MCDM's are the weighted sum model (WSM), the weighted product model (WPM) and the analytic hierarchy process (AHP). These models use numeric techniques to help decision makers choose among a set of alternatives. This is achieved on the basis of the impact of the alternatives on certain criteria and thereby on the overall utility of the decision makers. There are three steps in utilizing decision making techniques involving numerical analysis of alternatives (Triantaphyllou, 2000):

1. Determining the relevant criteria and alternatives.
2. Attaching numerical measures to the relative importance of the criteria and to the impacts of the alternatives on these criteria.
3. Processing the numerical values to determine a ranking of each alternative.

In this thesis, the AHP method is used for selecting the best scenario for the short term, defined as 2012-2015 and the best scenario for the long term, defined as 2012-2030. Due to its pair-wise comparisons, AHP allows personal judgments and enhances the precision of results. It lets users assess the relative weight of multiple criteria or multiple options against given criteria in an intuitive manner. AHP provides a proven, effective means to deal with complex decision making and can assist in identifying and weighting criteria, analyzing the data collected and expediting the decision making process.

Analytic Hierarchy Process

According to Saaty, to make a decision in an organized way using AHP to generate priorities, we need to decompose the decision into the following steps (Saaty, Decision Making With The Analytic Hierarchy Process, 2008).

1. Define the problem and determine the kind of knowledge sought.
2. Structure the decision hierarchy from the top with the goal of the decision, then the objectives from a broad perspective, through the intermediate levels (criteria on which subsequent elements depend) to the lowest level (which usually is a set of the alternatives).

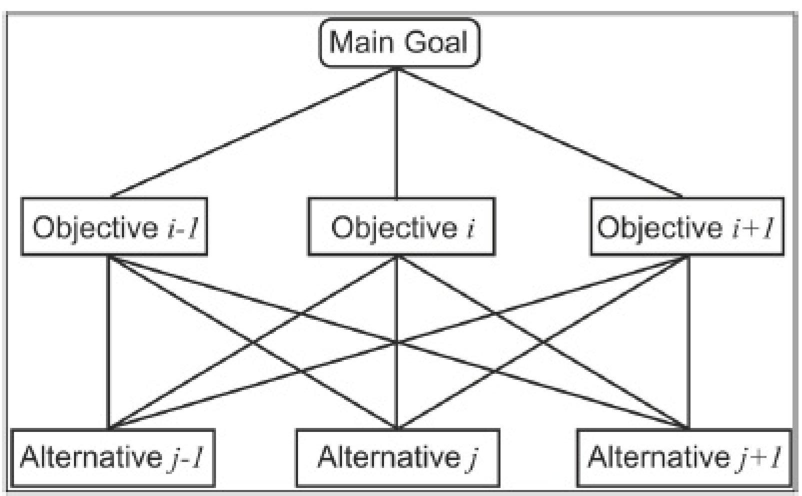

Figure 19 AHP Hierarchy of Goals, Objectives and Alternatives
(Dalalah, AL-Oqla, & Hayajneh, 2010)

3. Construct a set of pair-wise comparison matrices. Each element in an upper level is used to compare the elements in the level immediately below with respect to it.

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \vdots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} = \begin{bmatrix} w_1/w_1 & \cdots & w_1/w_n \\ \vdots & \vdots & \vdots \\ w_n/w_1 & \cdots & w_n/w_n \end{bmatrix}$$

Figure 20 Pair-wise Comparison Matrix

(Dalalah, AL-Oqla, & Hayajneh, 2010)

4. Use the priorities obtained from the comparisons to weight the priorities in the level immediately below. Do this for every element. Then for each element in the level below add its weighted values and obtain its overall or global priority. Continue this process of weighting and adding until the final priorities of the alternatives in the bottom most level are obtained.

To make comparisons, it requires a scale of numbers that indicates how many times more important or dominant one element is over another element with respect to the criterion or property, with respect to which element they are compared. Figure 21 exhibits this scale.

Intensity of Importance on an absolute scale	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgement strongly favor one activity over another
7	Very strong importance	An activity is strongly favored and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2 , 4 , 6 , 8	Intermediate values between the two adjacent judgments	When compromise is needed
Reciprocals	If activity i has one of the above numbers assigned to it when compared with activity j , then j has the reciprocal value when compared with i	
Rationals	Ratios arising from the scale	If consistency were to be forced by obtaining n numerical values to span the matrix

Figure 21 The Fundamental Scale

(Saaty, 1990)

The AHP Theory

The mathematical basis of the AHP is explained below (Coyle, 2004);

Consider n elements to be compared, $C_1 \ldots C_n$ and denote the relative 'weight' (or priority or significance) of C_i with respect to C_j by a_{ij} and form a square matrix $A=(a_{ij})$ of order n with the constraints that $a_{ij} = 1/a_{ji}$, for $i \neq j$, and $a_{ii} = 1$, all $_i$. Such a matrix is said to be a reciprocal matrix.

The weights are consistent if they are transitive, that is $a_{ik} = a_{ij}a_{jk}$ for all i, j, and k. Such a matrix might exist if the a_{ij} are calculated from exactly measured data. Then find a vector ω of order n such that $A_{\omega} = \lambda_{\omega}$. For such a matrix, ω is said to be an eigenvector (of order n) and λ is an eigenvalue. For a consistent matrix $\lambda = n$.

For matrices involving human judgment, the condition $a_{ik} = a_{ij}a_{jk}$ does not hold as human judgments are inconsistent to a greater or lesser degree. In such a case the ω vector satisfies the equation $A_{\omega}= \lambda_{max\omega}$ and $\lambda_{max} \geq n$. The difference, if any, between λ_{max} and n is an indication of the inconsistency of the judgments. If $\lambda_{max} = n$ then the judgments have turned out to be consistent. Finally, a Consistency Index can be calculated from $(\lambda_{max-n})/(n-1)$. That needs to be assessed against judgments made completely at random and Saaty has calculated large samples of random matrices of increasing order and the Consistency Indices of those matrices. A true Consistency Ratio is calculated by dividing the Consistency Index for the set of judgments by the Index for the corresponding random matrix. Saaty suggests that if that ratio exceeds 0.1 the set of judgments may be too inconsistent to be reliable. In practice, CRs of more than 0.1 sometimes have to be accepted. A CR of 0 means that the judgments are perfectly consistent.

Selecting the Best Short-Term and Long-Term Scenarios for CNG Use in the Transportation Sector via AHP

We'll follow Saaty's four step organized method to generate priorities to make decisions about the possible best short-term and long-term usages of compressed natural gas in the US transportation sector using Analytic Hierarchy Process. The analyses for short term and long term will be explained separately.

Step 1: Define the problem and determine the kind of knowledge sought.

Problem: What is the best ‘short-term scenario’ for CNG use in the US transportation sector? We’d like to make a decision about which vehicle types or combination of vehicle types could yield the highest benefit for the U.S. with respect to decision criteria explained below in the short term defined as 2012-2015.

Step 2: Structure the decision hierarchy from the top with the goal of the decision, then the objectives from a broad perspective, through the intermediate levels (criteria on which subsequent elements depend) to the lowest level (which usually is a set of the alternatives).

As mentioned above, our goal is to achieve maximum benefit from using CNG in the transportation sector. In order to measure this benefit we will define two objectives, positive environmental impact (P.E.I) and increased energy independency (I.E.I). P.E.I. represents the percentage of targeted CO_2 reduction from relevant CO_2 emission quantity through the proposed alternatives, the target being president Obama’s 25 November 2009 announcement of US Emission Target for Copenhagen (Office of the Press Secretary, 2009). I.E.I. refers to the percentage of targeted oil dependency reduction. The target for I.E.I. is defined by the National Oil Independence Goal, also cited as the Energy Security Act 5 of 2011 (Govtrack.us, 2011). These targets will be explained in detail in the target achievements section. As for the alternatives, four scenarios are proposed based on selected vehicle type’s different current fuel type usages and different utilization purposes for these vehicles. Four scenarios are presented below, explaining selected vehicle types:

Scenario A: 1/3 of all highway vehicles, trains and water vessels. Motorcycles are not considered to be a part of highway vehicles due to their limited fuel storage capacity. In this scenario, an inclusive combination of all vehicle types is projected. In this way, screening the effect of widespread usage of CNG is aimed.

Scenario B: Medium/heavy trucks, buses, trains and water vessels. The impact of using CNG in vehicles other than the residential needs is sought in scenario B to see the influence of CNG as a fuel for cargo and public transportation purposes.

Scenario C: 1/2 of all Trucks (light, medium and heavy), buses, trains and water vessels. Since using CNG as a fuel for vehicles needs greater fuel storage space on the vehicles according to current technology, the purpose of designing the combination for this scenario is to show the effect of utilization CNG as a fuel for the vehicles which don't have critical on board space limitations.

Scenario D: 1/2 of all light vehicles (cars and light trucks). The main idea behind the design of scenario D is to reflect the impact of CNG utilization as a fuel for residential vehicles, since they are the leading actor in total transportation energy consumption. Besides, it is aimed to be understood if it should be an objective to motivate regular people to switch to CNG.

The decision hierarchy structure containing these alternatives and attributes are shown in figure 22 schematically. Here, we want to find out which of the scenarios yields the most benefit in terms of the criteria positive environmental impact and increased energy independency.

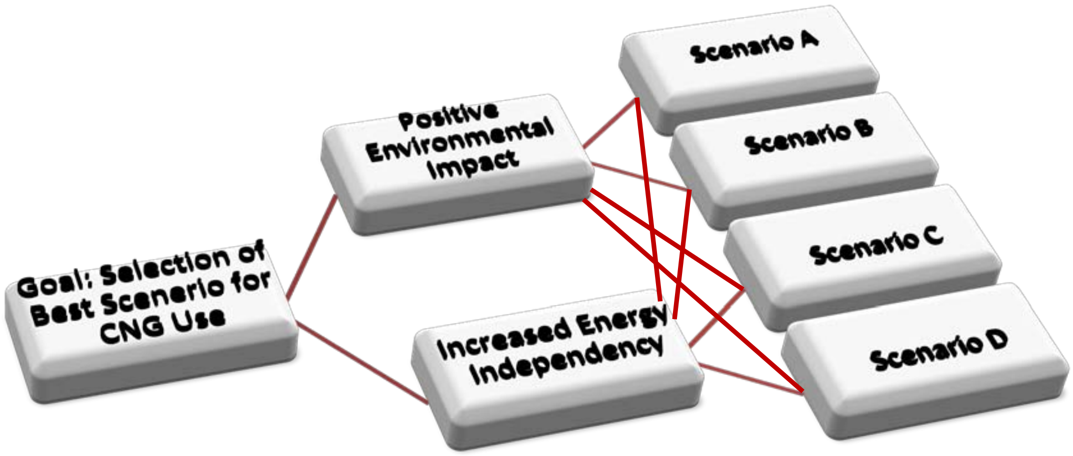

Figure 22 The Decision Hierarchy Structure

Step 3: Construct a set of pair-wise comparison matrices. Each element in an upper level is used to compare the elements in the level immediately below with respect to it.

Since we don't have decision makers' importance assessment for the two decision criteria, we follow a method of using all possible main values (1-3-5-7-9) from Saaty's fundamental scale and show the results for all of them. In this way, the decision maker or reader could make his own assessment and view the pre-calculated results. Possible assessments based on decision makers' possible evaluations are presented below:

Assessment 1: I.E.I. has extreme importance compared to P.E.I. The evidence favoring increased energy independency (I.E.I.) over positive environmental impact (P.E.I.) is of the highest possible order of affirmation.

Assessment 2: I.E.I. has very strong importance compared to P.E.I. I.E.I. is strongly favored and its dominance demonstrated in practice.

Assessment 3: I.E.I. has essential or strong importance compared to P.E.I. Experience and judgment strongly favor I.E.I. over P.E.I.

Assessment 4: I.E.I. has moderate importance compared to P.E.I. Experience and judgment slightly favor I.E.I. over P.E.I.

Assessment 5: I.E.I. and P.E.I have equal importance. Both of them contribute equally to the objective.

Assessment 6: P.E.I. has moderate importance compared to I.E.I. Experience and judgment slightly favor P.E.I. over I.E.I.

Assessment 7: P.E.I. has essential or strong importance compared to I.E.I. Experience and judgment strongly favor P.E.I. over I.E.I.

Assessment 8: P.E.I. has very strong importance compared to I.E.I. P.E.I. is strongly favored and its dominance demonstrated in practice.

Assessment 9: P.E.I. has extreme importance compared to I.E.I. The evidence favoring I.E.I. over P.E.I. is of the highest possible order of affirmation.

An example of pair-wise comparison matrices based on the assessments above is presented in table 1. The computed eigenvector or priorities, denoted as p(P.E.I.) and p(I.E.I.), give the relative ranking of decision criteria. The values denoted as m(P.E.I.) and m(I.E.I.) represent the same weighting before normalization of priorities. Calculating eigenvectors is done by multiplying together the entries in each row of the matrix and then taking the n^{th} root of that product, which is taking the geometric mean.

Normalization of the weights is done by proportioning the eigenvector value of the relevant criteria to the sum of the eigenvector values.

Assess. 1	P.E.I.	I.E.I.			Priorities	
P.E.I.	1	0.111	m(P.E.I)=	0.333	p(P.E.I)=	0.10
I.E.I.	9	1	m(I.E.I)=	3	p(I.E.I)=	0.90

Table 1 A Pair-wise Comparison Matrix

The m(P.E.I.), m(I.E.I) and p(P.E.I.), p(I.E.I) values are computed as shown in the below example:

For assessment 1:

m(P.E.I.) = $\sqrt[2]{\begin{array}{l} Intensity\ of\ importance\ value(P.E.I.)\ relative\ to\ (P.E.I.) \\ * Intensity\ of\ importance\ value(I.E.I.)\ relative\ to\ (P.E.I.) \end{array}}$

m(P.E.I.) = $\sqrt[2]{1 * 0.111}$ = 0.333

m(I.E.I.) = $\sqrt[2]{\begin{array}{l} Intensity\ of\ importance\ value(P.E.I.)\ relative\ to\ (I.E.I.) \\ * Intensity\ of\ importance\ value(I.E.I.)\ relative\ to\ (I.E.I.) \end{array}}$

m(I.E.I.) = $\sqrt[2]{9 * 1}$ = 3

Since in assessment 1 I.E.I has extreme importance compared to P.E.I., when calculating m(P.E.I.) the intensity of importance values are 1 and 0.111 respectively and when calculating m(I.E.I.) the intensity of importance values are 9 and 1 respectively according to the Saaty's fundamental scale in figure 21 . Degrees of roots are 2 in these calculations, because we are taking the geometric means of two numbers.

p(P.E.I.) = $\mathrm{m(P.E.I.)}/(\mathrm{m(P.E.I.)} + \mathrm{m(I.E.I.)})$

p(P.E.I.) = $0.333/(3 + 0.333)$ = 0.10

$p(\text{I.E.I.}) = m(\text{I.E.I.})/(m(\text{P.E.I.}) + m(\text{I.E.I.}))$

$p(\text{I.E.I.}) = 3/(3 + 0.333) = 0.90$

Calculating priority values p(P.E.I.) and p(I.E.I.) is a globalization process which makes the pair-wise weights of criteria for relative assessment sum up to 1. This is obtained by dividing the relative m value by the sum of two m values. For assessment 1, we are using 0.333 for m(P.E.I.) and 3 for m(I.E.I.) since we obtained these values in the previous calculations. As a result, under the conditions of assessment 1, we conclude that the priority of positive environmental impact is 10% where the priority of increased energy independence is 90%. Priorities relative to the other eight assessments are obtained in the same way.

Step 4: Use the priorities obtained from the comparisons to weight the priorities in the level immediately below. Do this for every element. Then for each element in the level below add its weighted values and obtain its overall or global priority. Continue this process of weighting and adding until the final priorities of the alternatives in the bottom most level are obtained.

The method used for calculating eigenvectors for scenarios' weightings according to relative decision criteria is similar to the calculation of pair-wise comparison matrices of decision criteria. This time pair-wise weights are determined by their target achievement values by proportioning them to each other, since those values constitute the relative importance of each scenario, according to relevant decision criteria. Target achievement values are used as given here. Details about calculating the target achievement values, which are provided in table 2 for the short-term, are given after the steps of analytic hierarchy process are completed with the intention of concept integrity.

Calculated Achievements	P.E.I.	I.E.I.
Scenario A	38.43	56.61
Scenario B	41.56	55.74
Scenario C	37.97	54.31
Scenario D	37.01	57.26

Table 2 Calculated Target Achievements for the short-term

When calculating m(P.E.I.), the ratios of calculated target achievement values, shown in table 2, are used to find each comparison result of scenario A vs. all scenarios, one at a time. So the numbers in the m(P.E.I.) formula are calculated like this:

$$Comparison\ result\ of\ scenario\ A\ vs\ A\ with\ respect\ to\ P.E.I = \frac{38.43}{38.43} = 1$$

$$Comparison\ result\ of\ scenario\ A\ vs\ B\ with\ respect\ to\ P.E.I = \frac{38.43}{41.56} = 0.925$$

$$Comparison\ result\ of\ scenario\ A\ vs\ C\ with\ respect\ to\ P.E.I = \frac{38.43}{37.97} = 1.012$$

$$Comparison\ result\ of\ scenario\ A\ vs\ D\ with\ respect\ to\ P.E.I = \frac{38.43}{37.01} = 1.039$$

The comparison results used for obtaining m(I.E.I.) are calculated in the same way like this:

$$Comparison\ result\ of\ scenario\ A\ vs\ A\ with\ respect\ to\ I.E.I = \frac{56.61}{56.61} = 1$$

$$Comparison\ result\ of\ scenario\ A\ vs\ B\ with\ respect\ to\ I.E.I = \frac{56.61}{55.74} = 1.016$$

$$Comparison\ result\ of\ scenario\ A\ vs\ C\ with\ respect\ to\ I.E.I = \frac{56.61}{54.31} = 1.042$$

$$Comparison\ result\ of\ scenario\ A\ vs\ D\ with\ respect\ to\ I.E.I = \frac{56.61}{57.26} = 0.989$$

The m(P.E.I.) and m(I.E.I.) values obtained by geometric mean of the relevant numbers are calculated above. Degrees of roots are 4 in these calculations, because we are taking the geometric means of four numbers.

For scenario A with respect to criteria P.E.I. and I.E.I.:

$$m(P.E.I.) = \sqrt[4]{\begin{array}{l} Comparison\ result\ of\ scenario\ A\ vs\ A\ with\ respect\ to\ P.E.I \\ * Comparison\ result\ of\ scenario\ A\ vs\ B\ with\ respect\ to\ P.E.I \\ * Comparison\ result\ of\ scenario\ A\ vs\ C\ with\ respect\ to\ P.E.I \\ * Comparison\ result\ of\ scenario\ A\ vs\ D\ with\ respect\ to\ P.E.I \end{array}}$$

m(P.E.I.) = $\sqrt[4]{1 * 0.925 * 1.012 * 1.039}$ = 0.993

$$m(I.E.I.) = \sqrt[4]{\begin{array}{l} Comparison\ result\ of\ scenario\ A\ vs\ A\ with\ respect\ to\ I.E.I \\ * Comparison\ result\ of\ scenario\ A\ vs\ B\ with\ respect\ to\ I.E.I \\ * Comparison\ result\ of\ scenario\ A\ vs\ C\ with\ respect\ to\ I.E.I \\ * Comparison\ result\ of\ scenario\ A\ vs\ D\ with\ respect\ to\ I.E.I \end{array}}$$

m(I.E.I.) = $\sqrt[4]{1 * 1.016 * 1.042 * 0.989}$ = 1.012

The p(P.E.I.) and p(I.E.I.) values are computed as shown in below example:

p(P.E.I.) = $0.933/(0.933 + 1.074 + 0.981 + 0.956)$ = 0.2480

p(I.E.I.) = $1.012/(1.012 + 0.996 + 0.970 + 1.023)$ = 0.2528

Calculating priority values p(P.E.I.) and p(I.E.I.) is a globalization process which makes the weights of a scenario for relative criteria sum up to 1. This is obtained by dividing the relative m value by the sum of all four m values. For scenario A, we are using the priority value of 0.933 as calculated and explained above and other priority values of 1.074, 0.981 and 0.956 calculated in the same way for p(P.E.I.). Again for scenario A, we are using the priority value of 1.012 as calculated and explained above and other priority values of 0.996, 0.970 and 1.023 calculated in the same way for p(I.E.I.). As a result, we conclude that the priority of scenario A is 24.80% with respect to positive environmental impact where the priority of scenario A is 25.28% with respect to increased energy independence. Priorities relative to the other three scenarios are obtained in the same way.

Overall priority of each scenario, according to each of the assessments, are obtained through multiplying priorities of each alternative for each decision criteria by their relevant assessment priorities and summing them up.

The overall priority of scenario A, according to assessment 1, is computed as shown below:

For assessment 1:

Ranking of Alternative A = (0.10*0.2480) + (0.90*0.2528) = 0.2524

Assessment 1 gives 0.10 priority to positive environmental impact criteria and scenario A has a 0.2480 priority with respect to this criterion where assessment 1 gives 0.90 priority to increased energy independency criteria and scenario A has a 0.2480 priority with respect to this criterion. As a result, under the assumptions of assessment 1, the overall priority of scenario A is 0.2524 or 25.24%. Overall priorities for the other three scenarios related to assessment 1, and each of the priorities for four scenarios related to the rest of the assessments are calculated in the same way.

In order to test the consistency of decision makers' knowledge, an inconsistency test is required as it is explained in the AHP Theory section. Since the order of the matrix is 2 (n = 2) in this analysis, we will not be doing a consistency analysis. In figure 23, which is The Average Random Consistency Index of a sample size of 500 matrices obtained by Saaty, the order of the random matrix (upper row) and corresponding index of consistency for random judgments (lower row) can be seen. For n = 2 the corresponding index of consistency for random judgments is 0, which means inconsistency is not an issue for the 2 x 2 matrix of scores.

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Figure 23 Random Index for the criteria used in decision making process

(Saaty, 1980)

Target Achievements

In order to explain target achievement calculations, which are to be declared after the completion of the AHP steps, relevant data is needed. To understand how much each of the vehicle type is contributing to the energy consumption, the data that is shown in figure 24 is obtained from the Center for Transportation Analysis Energy and Transportation Science Division. The values in the table presents the annual consumption of each vehicle type in T (trillion) Btu. Using these data, current energy consumption of each alternative by fuel type, as well as total energy consumptions of the alternatives are calculated as shown below. In this way, we could understand how much of the imported oil will be replaced by CNG, indicating the increased energy independence values. Vehicles powered by electricity are not considered for replacement since they are themselves alternative to petroleum based fuels.

Scenario A: 1/3 of All Highway Vehicles and Trains and water vessels. As explained before, motorcycles are not included because of their limited fuel storage capacity.

Energy consumption for gasoline:

$$(1/3) * (8761.4 + 7221.3 + 7.8 + 611.5 + 198.8) = 5600.27\ T\ Btu$$

Energy consumption for diesel:

$$(1/3) * (49.6\ + 341.8\ + 169.5\ + 5452.7\ + 468.4\ + 253.0) = 2245\ T\ Btu$$

Energy consumption for liquefied petroleum gas:

$$(1/3) * (45.0\ + 20.3)\ = 21.77\ T\ Btu$$

Energy consumption for residual fuel oil:

$$(1/3) * (839.4)\ = 279.80\ T\ Btu$$

Total current energy consumption for Scenario A:

$$5600.27\ + 2245\ + 21.77\ + 279.80 = 8146.84\ T\ Btu$$

To be able to measure the target achievements we have to know the targets and the current situations. The Energy Security Act 5 of 2011 shows the target for energy independency. In this bill, it is stated that it is the goal of the United States to reduce oil consumption by the quantity that is equal to or greater than the quantity of oil imported by the United States from outside of North America by calendar year 2030 (as compared to the rate of oil consumption projected for calendar year 2030 as of the date of enactment of this Act). According to the Energy Information Administration, the U.S. net imports of oil is 9,441,000 bbls (barrels) per day for 2010, 2,302,000 bbls of which is from Canada and 837,000 bbls of which is from Mexico (Energy Information Administration, 2011). As the U.S. oil trade partners inside of North America, Canada and Mexico are taken into account for the calculations as the only countries that oil trade will continue. It is assumed that oil import quantities from these countries as well as U.S. domestic consumption quantity will be the same as 2010 for the timeframes defined as short-term and long-term in this study. On a yearly basis, import values given above can be interpreted as 3,445,97M (million) bbls of total net imports, 840.23 M bbls from

Canada and 305.51 M bbls from Mexico. This means, as of 2010, Canada and Mexico's share (1145.74 M bbls) in total net oil imports is 33.25%. Total oil consumption of the U.S. is 36.96 Q Btu in 2010 (U.S. Cencus Bureau, 2012).

	Gasoline	Diesel fuel	LPG	Jet fuel	Fuel oil	Nat. gas	Electricity	Total
HIGHWAY	**16,661.4**	**6,013.6**	**65.3**			**22.0**	**0.7**	**22,763.0**
Light vehicles	**16,042.1**	**391.4**	**45.0**			**0.0**	**0.0**	**16,478.5**
Cars	8,761.4	49.6						8,811.0
Light trucks	7,221.3	341.8	45.0					7,608.1
Motorcycles	59.4							59.4
Buses	**7.8**	**169.5**	**0.0**			**22.0**	**0.7**	**200.0**
Transit	0.8	68.3	0.0			22.0	0.7	91.8
Intercity		31.4						31.4
School	7.0	69.9						76.9
Medium/heavy trucks	**611.5**	**5,452.7**	**20.3**					**6,084.5**
NONHIGHWAY	**237.1**	**721.4**	**0.0**	**2,099.3**	**839.4**	**616.8**	**312.2**	**4,826.1**
Air	**38.2**	**0.0**	**0.0**	**2,099.3**	**0.0**	**0.0**	**0.0**	**2,137.5**
General aviation	38.2			182.3				220.6
Domestic air carriers				1,530.8				1,530.8
International air carriers				386.2				386.2
Water	**198.8**	**253.0**			**839.4**			**1,291.3**
Freight		206.2			839.4			1,045.6
Recreational	198.8	46.8						245.6
Pipeline	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**616.8**	**240.1**	**856.9**
Rail	**0.0**	**468.4**	**0.0**	**0.0**	**0.0**	**0.0**	**72.1**	**540.4**
Freight (Class I)		446.6						446.6
Passenger		21.7					72.1	93.8
Transit		0.0					47.8	47.8
Commuter		13.2					18.4	31.6
Intercity		8.6					5.8	14.4
TOTAL HWY & NONHWY	**16,898.5**	**6,735.0**	**65.3**	**2,099.3**	**839.4**	**638.7**	**312.9**	**27,589.0**

Figure 24 Domestic Consumption of Transportation Energy by Mode and Fuel Type

(Center for Transportation Analysis Energy and Transportation Science Division, 2011)

As we make our calculations based on energy, measured by Btu, it will be very convenient to convert the bbl values above to Btu. To accomplish this we need the composition of the petroleum products and their relevant heating values. The composition of petroleum products is collected from the Energy Information Agency (Energy Information Administration, 2011) and heating values are obtained from Environmental Protection Agency (Environmental Protection Agency, 2004) and M.I.T (M.I.T., 2007), figure 25. An average heating value of 126,802 Btu/gal is computed by averaging the heating values of fuel types with respect to their relevant consumption percentages. Since 1 bbl of petroleum is equal to 42 gallons, the average heating value of petroleum consumed in the U.S. is 5.3257 M Btu/bbl (126,802*42). This value helps us convert the values measured in bbls above as in the example below.

Conversion of bbl to Btu:

$$3{,}445{,}97 \text{ M bbls} * 5.3257 \text{ M } \frac{\text{Btu}}{\text{bbl}} = 18.35 \text{ Q Btu}$$

Delivered Energy Consumption, All Sectors, 2010	**Q BTU**	**% of Total**	**Heat. value (Btu/gal)**	
Liquefied Petroleum Gases	2.82	7.72	91,420	706,120
E85				
Motor Gasoline	17.17	47.03	124,340	5,847,488
Jet Fuel	3.14	8.60	135,000	1,161,052
Kerosene	0.03	0.08	135,000	11,093
Distillate Fuel Oil	7.8	21.36	138,690	2,962,975
Residual Fuel Oil	1.02	2.79	149,690	418,197
Liquid Fuels Subtotal	36.51	100	126,802	
Average				126,802

Figure 25 Average Heating Value for Transportation Fuels

(EIA, EPA, MTI)

Total net oil imports of the U.S. in 2010 are 3,445,97M bbls. By multiplying it to the relevant heating value of 5.3257 M Btu/bbl we get 18.35 Q Btu of total net imports expressed in energy units. In the same way, the U.S. total imports of 1145.74 M bbls from inside of North America is calculated to be 6.1 Q Btu, which means imports from outside of the North America, as referred to in Energy Security Act, are 12.25 Q Btu by 2010. Oil consumption projections as of the date of enactment of the Act by Energy Information administration (Energy Information Administration, 2011) shows that oil consumption in the U.S. will be 39.1 Q Btu in 2015, 2.14 Q Btu more than 2010 consumption of 36.96 Q Btu as given above, and 40.55 Q Btu in 2030, 3.59 Q Btu more than 2010 consumption.

The termination dates for our defined short-term and long term are 2015 and 2030, respectively. U.S. imports 12.25 Q Btu outside from North America, as of the date of enactment of Energy Security Act and will consume 2.14 Q Btu more in 2015 and 3.59 Q Btu more in 2030. It is assumed that, domestic oil production and oil import quantities from Canada and Mexico will be the same as 2010 for the timeframes defined as short-term and long-term, as stated above. Based on these values and assumptions, the U.S. targeted oil import reductions are calculated to be 14.39 Q Btu (12.25 + 2.14) for 2015 and 15.84 Q Btu (12.25 + 3.59) for 2030. Target achievements with respect to I.E.I. are calculated by dividing the increased energy independence values relevant to each scenario by targeted oil imports reductions. For scenario A under short-term conditions, the calculated target achievement is (8146.84 / 14390) * 100 = 56.11%. The targeted oil import reduction that is computed as 14.39 Q Btu and is converted to 14390 T Btu for the conformance to I.E.I value is 8164.84 T Btu.

CO_2 emissions reduction target is constituted by president Obama's 25 November 2009 announcement of US Emission Target for Copenhagen. In his announcement, president Obama set the goals of total CO_2 emissions reduction by 17% below 2005 levels in 2020 and by 42% below 2005 levels in 2030. The 2005 level of CO_2 obtained from the Energy Information Administration is 6114.2 M metric tons or 13482.25 M lbs. With a 42% reduction from this value, the targeted emission level for 2030 is 7819.7 M lbs and with a 17% reduction from this value, the targeted emission level for 2020 is 11190.27 M lbs. Assuming a steady rate in emission reduction through 2020, the targeted emission level for 2015 could be calculated as 12622.76 M lbs.

The difference between the targeted emission levels and starting level gives us the emissions reduction targets, which are 859.49 M lbs and 5662.54 M lbs. for 2015 and 2030, respectively. Target achievements with respect to P.E.I for each scenario are calculated by dividing the calculated CO_2 reduction quantities by emission reduction targets for the relative timeframe. For scenario A under short-term conditions, the calculated target achievement is (331.195/ 859.49) * 100 = 38.43%. Target achievement values for the other scenarios could be calculated in the same way.

Calculated CO_2 reduction quantities are obtained via differencing the sum of the CO_2 emission level for currently used fuel types and the CO_2 emission level as a result of proposed CNG replacement. In order to accomplish this calculation we need CO_2 emission factors, in figure 26, for each fuel type. These factors show the quantity of CO_2 emission in lbs when 1 M (million) Btu of energy is consumed. The calculation of current CO_2 emission level for scenario A is presented below as an example.

For scenario A in the short-term:

Current CO_2 emissions for gasoline = CO_2 emission factor for gasoline * gasoline consumption according to scenario A in the short-term.

Current CO_2 emissions for gasoline = 154.91 $\frac{lbs}{M\ Btu}$ * (5,600.27 * 10^6) M Btu

Current CO_2 emissions for gasoline = 867,537.31 lbs.

A value of 5,600.27 T Btu, the calculation of which is given in the beginning of this section, is converted to (5,600.27 * 10^6) M Btu for the conformance to CO_2 emission factor value, which is 154.91 $\frac{lbs}{M\ Btu}$. After we finish current CO_2 emission calculations for other fuel types in this way, we can find the overall current CO_2 emission value for the relevant scenario by summing them up. For scenario A in the short-term, this value is 1,278,551 lbs. Calculation of the CO_2 emission level as a result of CNG replacement for scenario A is shown below as an example.

For scenario A in the short-term:

CO_2 emissions for CNG = CO_2 emission factor for CNG * total projected energy consumption according to scenario A in the short term

CO_2 emissions for CNG = 116.39 $\frac{lbs}{M\ Btu}$ * (8,146.84 * 10^6) M Btu

CO_2 emissions for CNG = 948,210 lbs

The value of 8,146.84 T Btu, which is given in the beginning of this section, is converted to (8,146.84 * 10^6) M Btu for conformance to a CO_2 emission factor value, which is 116.39 $\frac{lbs}{M\ Btu}$. When we subtract the CO_2 emission as a result of proposed CNG replacement from current CO_2 emission value we find CO_2 reduction quantities for relevant scenarios. For scenario A, this value is 330,341 lbs.

Fuel Type	CO_2 Emission Factors (lb CO_2/MMBtu)
Motor Gasoline	154.91
Diesel Fuel	160.3
LPG (average for fuel use)	138.75
Jet Fuel	154.69
Residual Fuel Oil (#5 & 6)	171.98
Natural Gas	116.39

Figure 26 CO_2 Emission Factors

(Environmental Protection Agency, 2004)

Target achievement calculations for the long-term are the same as the short-term calculations. As for the values, targeted oil dependency reduction and targeted CO_2 reduction values are the same for both timeframes. On the other hand, due to federal government's fuel efficiency target that affect all cars and light trucks in the long-term, projected current energy consumptions of the given scenarios are lower in the long-term which affects both targeted oil reduction values, directly, and CO_2 reduction quantities by changing current CO_2 emissions and scenario based CO_2 emissions. This difference is the result of the assumption based on president Obama's announcement of an agreement on projected fuel efficiency standards with thirteen major automakers which together account for over 90% of all vehicles sold in the United States (Office of the Press Secretary, 2011).

According to the proposed rules prepared by the Department of Transportation National Highway Traffic Safety Administration, based on the goals that are declared by the president, the new CO_2 emission standard for cars is 130.5 $\frac{grams}{mile}$ and the new CO_2

emission standard for light trucks is 159.1 $\frac{grams}{mile}$. In the same report the fuel economy standard for cars is a minimum 45.61 mpg and for light trucks it is 30.61 mpg. When we multiply the new emission standard for cars by the new fuel economy standard for cars we get the new emission standard for cars in grams for a gallon of fuel, which is 5952.11 $\frac{grams}{gal}$. After a simple conversion we could get 13.125 $\frac{lbs}{gal}$ CO_2. The value of the new emission standard for light trucks is calculated as 10.591 $\frac{lbs}{gal}$ CO_2 using the same method.

The CO_2 emission factor for gasoline is 154.91 $\frac{lbs}{M\ Btu}$ CO_2 and the heating value is 0.12434 $\frac{M\ Btu}{gal}$. When we multiply these two values we get the CO_2 emission in lbs for burning 1 gallon of gasoline. This value is 154.91 $\frac{lbs}{M\ Btu}$ CO_2 * 0.12434 $\frac{M\ Btu}{gal}$ = 19.262 $\frac{lbs}{gal}$ CO_2. The heating value of a fuel is a unique chemical property under constant conditions. Therefore, in order to get a new and better emission standard of 13.125 $\frac{lbs}{gal}$ CO_2 for cars powered by gasoline whose current emission standard is 19.262 $\frac{lbs}{gal}$, CO_2 the emission quantity for the same amount of heating value needs to be decreased. This could be done by using new technologies or changing design parameters of the cars if the fuel type remains the same. The reduction ratio of the emission quantity is equal to the ratio of the new emission standard to the old emission standard. As a result, to accomplish the new emission standard of 13.125 $\frac{lbs}{gal}$ CO_2 for gasoline powered cars, emission quantity for cars needs to be upgraded to $(13.125\ \frac{lbs}{gal}/19.262\ \frac{lbs}{gal}) * 154.91\ \frac{lbs}{M\ Btu}\ \mathrm{CO2} = 105.56\ \frac{lbs}{M\ Btu}\ \mathrm{CO2}$. This value is $85.18\ \frac{lbs}{M\ Btu}\ \mathrm{CO2}$ for gasoline powered light trucks. New emission quantities for cars and light trucks could be calculated in the same way for other fuel types.

For the long-term scenario calculations, these emission quantities are taken into consideration for current CO_2 emission calculations and proposed CNG replacement scenario CO_2 emission calculations. Determination of P.E.I. target achievements is done by using these values for cars and light trucks for the relevant scenario. They are also used for calculating energy consumption for cars and light trucks in the relevant scenario, thus allowing us to determine the I.E.I. target achievements.

IV. Analysis and Results

According to analytic hierarchy process assumptions, each of the decision criteria need to be compared to the rest of the criteria, one at a time, based on their relative importance from the decision makers point of view. In this study, we don't have decision maker's importance assessment for the two defined decision criteria, positive environmental impact and increased energy independency. Hence, we chose to follow a way of evaluating all possible relative importance assessments by using all possible main values (1-3-5-7-9) from Saaty's fundamental scale, and rank the scenarios for all of them. In this way, we are providing pre-calculating results allowing the decision maker or reader to observe the best short-term and long-term scenarios based on his own assessment.

In table 3, priorities of positive environmental impact and increased energy independency relative to the decision maker's importance assessments can be seen. With reference to this table, if a decision maker assesses the increased energy independency criterion as very strongly more important than positive environmental impact the priority of (P.E.I.) becomes 0.10, which means it is of 10% importance. With the same assessment, the priority of (I.E.I) becomes 0.90, which means it has 90% importance.

Assess. 1	P.E.I.	I.E.I.			Priorities	
P.E.I.	1	0.111	m(P.E.I)=	0.333	p(P.E.I)=	0.10
I.E.I.	9	1	m(I.E.I)=	3.000	p(I.E.I)=	0.90
Assess. 2	P.E.I.	I.E.I.			Priorities	
P.E.I.	1	0.143	m(P.E.I)=	0.378	p(P.E.I)=	0.13
I.E.I.	7	1	m(I.E.I)=	2.646	p(I.E.I)=	0.88
Assess. 3	P.E.I.	I.E.I.			Priorities	
P.E.I.	1	0.200	m(P.E.I)=	0.447	p(P.E.I)=	0.17
I.E.I.	5	1	m(I.E.I)=	2.236	p(I.E.I)=	0.83
Assess. 4	P.E.I.	I.E.I.			Priorities	
P.E.I.	1	0.333	m(P.E.I)=	0.577	p(P.E.I)=	0.25
I.E.I.	3	1	m(I.E.I)=	1.732	p(I.E.I)=	0.75
Assess. 5	P.E.I.	I.E.I.			Priorities	
P.E.I.	1	1	m(P.E.I)=	1	p(P.E.I)=	0.50
I.E.I.	1	1	m(I.E.I)=	1	p(I.E.I)=	0.50
Assess. 6	P.E.I.	I.E.I.			Priorities	
P.E.I.	1	3	m(P.E.I)=	1.732	p(P.E.I)=	0.75
I.E.I.	0.333	1	m(I.E.I)=	0.577	p(I.E.I)=	0.25
Assess. 7	P.E.I.	I.E.I.			Priorities	
P.E.I.	1	5	m(P.E.I)=	2.236	p(P.E.I)=	0.83
I.E.I.	0.2	1	m(I.E.I)=	0.447	p(I.E.I)=	0.17
Assess. 8	P.E.I.	I.E.I.			Priorities	
P.E.I.	1	7	m(P.E.I)=	2.646	p(P.E.I)=	0.88
I.E.I.	0.143	1	m(I.E.I)=	0.378	p(I.E.I)=	0.13
Assess. 9	P.E.I.	I.E.I.			Priorities	
P.E.I.	1	9	m(P.E.I)=	3.000	p(P.E.I)=	0.90
I.E.I.	0.111	1	m(I.E.I)=	0.333	p(I.E.I)=	0.10

Table 3 Pair-wise Comparison Matrices

Using the data obtained from the Center for Transportation Analysis Energy and Transportation Science Division that is shown in figure 24, current energy consumption of each alternative by fuel type, as well as total energy consumptions of the alternatives, are calculated. The benefit of these calculations is that the results exhibit how much each of the vehicle type is currently contributing to the energy consumption, which means how much of the imported oil will be replaced by CNG. These results help us get increased energy independence values in comparison with the import reduction targets for the short-term and the long-term. They are also used for comparing the alternatives with respect to this criterion. Total energy consumptions for four scenarios for both timeframes are provided below in table 4.

According to these values, in the short-term, scenario D has the highest target achievement rate, followed by scenario A, then Scenario B. Scenario C has the lowest contribution to decreasing energy dependency. This is simply the result of the differrence between total energy consumptions of the scenarios. In the long-term, although the combinations of scenarios doesn’t alter, their total energy consumptions vary compared to their short-term counterparts. This is because of the new proposed energy efficiency standards. Scenarios which involve a greater amount of light highway vehicle energy consumption, lose their advantage of contributing to energy security in the long-term, because new standards decrease the energy consumption of cars and light trucks. In parallel to this, scenario B has the highest target achievement rate, followed by scenario C, then Scenario A. Scenario D, which involves only light vehicles in its combination has the lowest contribution to decreasing energy dependency in the long-term.

Scenarios	Energy Consumption by Fuel Type T Btu					% of targeted oil dependency reduction (I.E.I)
	Gasoline	Diesel fuel	LPG	Res. fuel oil	Total	
Short Term						
Scenerio A :	5,600.27	2,245.00	21.77	279.80	8,146.84	56.61
Scenerio B :	818.10	6,343.60	20.30	839.40	8,021.40	55.74
Scenerio C :	4,019.70	3,342.70	32.65	419.70	7,814.75	54.31
Scenerio D :	8,021.05	195.70	22.50		8,239.25	57.26
Long Term						
Scenerio A :	3,907.26	2,213.19	18.44	279.80	6,426.02	39.87
Scenerio B :	818.10	6,343.60	20.30	839.40	8,043.40	49.82
Scenerio C :	3,219.59	3,304.83	27.66	419.70	6,982.79	43.30
Scenerio D :	5,451.83	147.98	17.51		5,617.33	34.89

Table 4 Energy Consumption by Fuel Type and I.E.I. values

Target achievement values are calculated based on CO_2 emission quantities of scenarios and emission reduction targets which are mandated by The Energy Security Act of 2011 for the two timeframes. Results can be seen in table 5. These results help us understand the contribution of each scenario to the positive environmental impact criterion. They are also used for comparing the alternatives with respect to this criterion. According to target achievement values, in the short-term, scenario B has the highest target achievement rate, followed by scenario A, then Scenario C. Scenario D has the lowest contribution to positive environmental impact.

In the long-term, scenario C has the highest target achievement rate, followed by scenario B, then Scenario A. Scenario D has the lowest contribution to positive environmental impact. The reason behind the difference of the two timeframes is the changing magnitude of the CO_2 reduction targets by time. Scenarios which involve a greater amount of light highway vehicle energy consumption, lose their advantage of contributing to emission reduction goals in the long-term, because new standards increase the CO_2 reduction standards of cars and light trucks.

Scenarios		CO_2 Emissions lbs					% of targeted emission reduction (P.E.I)
		Gasoline	Diesel fuel	LPG	Fuel oil	Total	
Short Term							
Scenerio A :	Current	867,537.31	359,873.50	3,020.13	48,120.00	1,278,550.94	38.43
	CNG	651,815.04	261,295.55	2,533.42	32,565.92	948,209.93	
	Reduction	215,722.27	98,577.95	486.70	15,554.08	330,341.01	
Scenerio B :	Current	126,731.87	1,016,879.08	2,816.63	144,360.01	1,290,787.59	41.56
	CNG	95,218.66	738,331.60	2,362.72	97,697.77	933,610.75	
	Reduction	31,513.21	278,547.48	453.91	46,662.25	357,176.84	
Scenerio C :	Current	622,691.73	535,834.81	5,233.80	72,180.01	1,237.22	37.97
	CNG	467,852.88	389,056.85	3,800.13	48,848.88	910.84	
	Reduction	154,838.84	146,777.96	1,433.66	23,331.12	326.38	
Scenerio D :	Current	1,242,540.86	31,370.71	3,121.88		1,277,033.44	37.01
	CNG	933,570.01	22,777.52	2,618.78		958,966.31	
	Reduction	308,970.85	8,593.19	503.10		318,067.13	
Long Term							
Scenerio A :	Current	605,272.89	354,774.04	2,558.93	48,120.00	1,010,725.86	6.08
	CNG	377,212.79	253,900.25	2,525.40	32,565.92	666,204.36	
	Reduction	228,060.10	100,873.79	33.53	15,554.08	344,521.50	
Scenerio B :	Current	126,731.87	1,016,879.08	2,816.63	144,360.01	1,290,787.59	6.31
	CNG	95,218.66	738,331.60	2,362.72	97,697.77	933,610.75	
	Reduction	31,513.21	278,547.48	453.91	46,662.25	357,176.84	
Scenerio C :	Current	498,747.06	529,764.11	4,434.55	72,180.01	1,105,125.73	6.83
	CNG	287,015.47	379,421.83	3,210.45	48,848.88	718,496.63	
	Reduction	211,731.59	150,342.28	1,224.10	23,331.12	386,629.09	
Scenerio D :	Current	844,543.40	23,721.52	2,430.08		870,695.00	5.98
	CNG	518,209.86	11,684.58	2,029.09		531,923.53	
	Reduction	326,333.54	12,036.94	400.98		338,771.47	

Table 5 CO_2 Emissions by Fuel Type and P.E.I. values

The priorities of each scenario are calculated to rank them with respect to each criterion. These priorities are shown in table 6 for the short-term and table 7 for the long-term. According to these results, scenario B has the top priority with respect to P.E.I.

criterion in the short-term, followed by scenario A, scenario C and scenario D, respectively. In other words, using CNG for cargo and public transportation purposes provides the highest contribution to reduce the environmental worries in the short-term. With respect to I.E.I. criterion in the short-term, scenario D has the top priority, followed by scenario A, scenario B and scenario C, respectively. Utilizing CNG for the fuel requirement for residential vehicles contributes more to the energy security objective than the other proposed utilization options, in the short-term.

In the long-term, with respect to P.E.I. criterion scenario C has the top priority, followed by scenario B, scenario A and scenario D, respectively. Implementation of CNG as a fuel for the vehicles which don't have critical on board space limitation yields the highest benefit when only environmental worries are taken into consideration, in the long-term. Scenario B has the top priority, with respect to I.E.I. criterion in the long-term followed by scenario A, scenario C and scenario D, respectively. We can say that, using CNG for cargo and public transportation purposes helps the most to achieve energy security goals.

P.E.I.	Scenario A	Scenario B	Scenario C	Scenario D			Priorities	
Scenario A	1.000	0.925	1.012	1.039	m(A)=	0.993	p(A)=	0.2480
Scenario B	1.081	1.000	1.094	1.123	m(B)=	1.074	p(B)=	0.2682
Scenario C	0.988	0.914	1.000	1.026	m(C)=	0.981	p(C)=	0.2450
Scenario D	0.963	0.891	0.975	1.000	m(D)=	0.956	p(D)=	0.2388
I.E.I.	Scenario A	Scenario B	Scenario C	Scenario D			Priorities	
Scenario A	1.000	1.016	1.042	0.989	m(A)=	1.012	p(A)=	0.2528
Scenario B	0.985	1.000	1.026	0.974	m(B)=	0.996	p(B)=	0.2489
Scenario C	0.959	0.974	1.000	0.948	m(C)=	0.970	p(C)=	0.2425
Scenario D	1.011	1.027	1.054	1.000	m(D)=	1.023	p(D)=	0.2557

Table 6 Comparison Results of the Alternatives for the short-term

P.E.I.	Scenario A	Scenario B	Scenario C	Scenario D				
Scenario A	1.000	0.964	0.890	1.017	m(A)=	0.966	p(A)=	0.2413
Scenario B	1.037	1.000	0.924	1.055	m(B)=	1.003	p(B)=	0.2503
Scenario C	1.123	1.083	1.000	1.142	m(C)=	1.086	p(C)=	0.2711
Scenario D	0.984	0.948	0.876	1.000	m(D)=	0.951	p(D)=	0.2373
I.E.I.	Scenario A	Scenario B	Scenario C	Scenario D				
Scenario A	1.000	0.800	0.921	1.143	m(A)=	0.958	p(A)=	0.2375
Scenario B	1.250	1.000	1.151	1.428	m(B)=	1.197	p(B)=	0.2968
Scenario C	1.086	0.869	1.000	1.241	m(C)=	1.040	p(C)=	0.2579
Scenario D	0.875	0.700	0.806	1.000	m(D)=	0.838	p(D)=	0.2078

Table 7 Comparison Results of the Alternatives for the long-term

Calculated overall rankings of scenarios based on decision maker's every possible assessment are presented in the following tables, table 8 for the short-term and table 9 for the long-term. These are the final results we aimed to obtain from the analytic hierarchy process. We can draw conclusions based on these ranking values, because they show the ranking of each scenario for each assessment, and for each defined timeframe. According to these results, for the short-term period, scenario D is preferable to other scenarios if a decision maker gives increased energy independency at least essential or strong importance compared to positive environmental impact. If he gives I.E.I. less than essential or strong importance compared to I.E.I., scenario B becomes preferable. Therefore, we could say that in the short-term period, the best CNG scenario shifts from utilization of CNG for residential vehicle fuel needs to cargo and public transportation purposes as the decision maker's main concern shifts from energy security to environmental issues.

When it comes to the long-term period, scenario B is preferable to other scenarios if a decision maker favors increased energy independency by any magnitude or perceives the two criteria's importance equal. If he or favors P.E.I. scenario C becomes preferable. Hence, we could say that in the long-term, using CNG for cargo and public transportation purposes yields the most benefit from CNG utilization if the most important issue is energy security or both objectives have the same importance for the decision maker. Otherwise, using CNG as a fuel for vehicles which don't have critical on board space limitations becomes the best scenario for the long-term. Scenario D is the lowest ranking alternative in all of the assessments, which could mean that utilization of CNG as a residential vehicle provides the lowest benefit of all in the long-term. This is mainly because of the federal government's new fuel efficiency standards, affecting only cars and light trucks in the long term.

Assesments	Scenarios	Ranking
Assess. 1	A	0.2524
	B	0.2509
	C	0.2428
	D	0.2540
Assess. 2	A	0.2522
	B	0.2513
	C	0.2428
	D	0.2536
Assess. 3	A	0.2520
	B	0.2521
	C	0.2429
	D	0.2529
Assess. 4	A	0.2516
	B	0.2537
	C	0.2432
	D	0.2515
Assess. 5	A	0.2504
	B	0.2585
	C	0.2438
	D	0.2472

Assesments	Scenarios	Ranking
Assess. 6	A	0.2492
	B	0.2634
	C	0.2444
	D	0.2430
Assess. 7	A	0.2488
	B	0.2650
	C	0.2446
	D	0.2416
Assess. 8	A	0.2486
	B	0.2658
	C	0.2447
	D	0.2409
Assess. 9	A	0.2485
	B	0.2662
	C	0.2448
	D	0.2405

Table 8 Overall Ranking of Scenarios for the short-term

Assesments	Scenarios	Ranking
Assess. 1	A	0.2379
	B	0.2921
	C	0.2592
	D	0.2108
Assess. 2	A	0.2380
	B	0.2910
	C	0.2596
	D	0.2115
Assess. 3	A	0.2381
	B	0.2890
	C	0.2601
	D	0.2127
Assess. 4	A	0.2384
	B	0.2852
	C	0.2612
	D	0.2152
Assess. 5	A	0.2394
	B	0.2735
	C	0.2645
	D	0.2226

Assesments	Scenarios	Ranking
Assess. 6	A	0.2403
	B	0.2619
	C	0.2678
	D	0.2299
Assess. 7	A	0.2407
	B	0.2581
	C	0.2689
	D	0.2324
Assess. 8	A	0.2408
	B	0.2561
	C	0.2694
	D	0.2336
Assess. 9	A	0.2409
	B	0.2550
	C	0.2697
	D	0.2344

Table 9 Overall Ranking of Scenarios for the long-term

We can draw the conclusion that if the government's new fuel efficiency and emission standards could be implemented successfully, as assumed in the long-term period part of this work, they will have a great impact on light vehicles. In table 10, current fuel efficiency standards is obtained from the report prepared for congress by the Energy Policy, Resources, Science, and Industry division and they reflect standards for 2008 through 2010 (Energy Policy Resources, Science, and Industry Division, 2007). The target values for fuel efficiency is obtained from the supplemental report of intent prepared by the Environmental Protection Agency (Environmental Protection Agency, 2011) based on president Obama's fuel efficiency announcement of 2011 (Office of the Press Secretary, 2011).

Current CO_2 emission values are received from The Environmental Protection Agency's emission factors data sheet (Environmental Protection Agency, 2004) . The target values for CO_2 emissions are calculated as shown in chapter 3. It could be realized from the table that a significant development is projected for fuel efficiencies. The target of about 60% efficiency improvement for cars is drastic and is a matter of debate. Targeted CO_2 emission standards have the most impact on gasoline and diesel which requires a great development for cars and light trucks powered by these fuels.

	Standards for cars and Light Trucks			
	Fuel Efficiency Cars- L.Trucks (MPG)		CO_2 Emission Cars and L.Trucks (lb CO_2/ MM Btu)	
	Current	Target	Current	Target
Gasoline	27.50 / 23.50	45.61 / 30.19	154.91	105.56 / 85.18
Diesel	27.50 / 23.51	45.61 / 30.20	160.30	95.54 / 77.10
LPG	27.50 / 23.52	45.61 / 30.21	138.75	143.56 / 115.86
Natural Gas	27.50 / 23.53	45.61 / 30.22	116.39	103.30 / 83.58

Table 10 Fuel Efficiency and Emission Standards for Cars and Light Trucks

In the following chapter, findings of this study will be introduced for the purpose of drawing useful conclusions. Furthermore, our recommendations will be presented based on exhibited findings and conclusions.

V. Conclusions and Recommendations

In this chapter, we will review and provide answers to the research sub-questions that we posed in chapter 1. In this way, we will be able to address the main research question more confidently. Finally we will propose our recommendations.

Summary of Findings

For the purpose of providing a well structured explanation to the research question it is an effective and organized method to start with addressing explanatory questions. Here, we will try to give sound answers based on our literature review and calculations for this work.

Based on the current and projected supply of NG in the US, how much of the US transportation sector fuel requirement could 'possibly' be replaced by CNG? (Anecdotally – how much CNG would it take to replace all of the US transportation sector fuel requirement, and how long would it last?)

Considering the abundant domestic natural gas supply in the U.S., natural gas basically can replace all of the transportation sector fuel consumption for a long period of time. The U.S. future natural gas supply is projected as 2552 Tcf or 2,615.8 Q Btu. This amount is sufficient for 105 years according to current natural gas consumption of 24,8 Q Btu per year. If all of the transportation fuel requirement is replaced by CNG, it will require an additional 27.5 Q Btu per year. Under the assumption that these consumptions will hold the same, domestic supplies would be able to satisfy this total demand for 50 years. This assumes production and related infrastructure is established to meet this increased demand.

Based on current US infrastructure (and relatively low cost changes), how much of the US transportation sector fuel requirement could 'feasibly' be replaced by CNG?

To be able to answer this question, the bottlenecks of the natural gas supply system need to be identified. The natural gas supply system infrastructure is composed of production facilities, LNG import terminals, pipelines and refueling stations. As they are used for import purpose, LNG import terminals are not considered as a relevant element of the structure with respect to the aim of this study. With recent significant capacity additions pipelines have become a non-constraint for the supply system. Scarcity of refueling stations is a major problem for the delivery of natural gas. It can be identified as a limitation rather than a bottleneck. The small number of refueling stations in the U.S. is far from supporting the transportation sector. Assuming that we can refuel at home or effective solutions to this limitation are developed, the main bottleneck of the system reveals itself as production capacity.

Production capacity has 65% utilization on annual average, but in the peak demand time during winter the capacity is not sufficient to meet daily demand on some days. At this point, underground natural gas storage capacity takes action. This capacity is able to meet four times the peak time demand, based on historical data. Taking these facts into consideration, and assuming the current import rate of 10.9% will be stable, 55.66% of the annual transportation sector fuel requirement could be feasibly replaced by CNG. According to The Energy Security Act of 2011 requirements this ratio drops a little to 53.94%. If policy makers choose to use only domestic natural gas, 45.82% of total sector requirement could be feasibly replaced.

What are the current barriers to CNG as a transportation fuel replacement? What is the cost-benefit (to the individual and nation) of using CNG power vehicles? What is needed to make CNG cost effective, and what is the potential impact of that change?

There are some infrastructural limitations as mentioned in the previous question. Production capacity needs to be increased if a more common usage than feasible replacement ratios are desired. Underground storage capacity is the main storage utility for natural gas. It consists of depleted reservoirs and salt caverns. Any storage other than underground storage will require great investments, since natural gas cannot be stored in barrels like oil. Therefore, there is nothing to be done about storage capacity. Current pipeline capacity, with the significant investments over the last five years, is capable of meeting three times the highest daily demand. Refueling infrastructure and on-board storage capacity are the main barriers using CNG vehicles. Refueling station investments are expensive. Although the home refueling option does not put a great monetary burden on vehicle owners' shoulders, the range of the CNG powered vehicles are short and there is not enough refueling station infrastructure to support long distance travels. Besides, payback times of switching to CNG powered vehicles are not promising. This is the dilemma about common CNG usage as a transportation fuel. Fuel delivery companies do not want to invest a great amount of money while they are not forecasting a payback. On the other side, vehicle owners do not want to use a car that they cannot easily refuel.

At this point, policy makers should take action. If environmental concerns and energy security have great importance as they are declared to be, some incentives need to be proposed to each side. Tax incentives may reduce the payback times of CNG powered vehicles, motivating people to think about it. Subsidies may trigger natural gas production and delivery companies as well as vehicle production companies. In this perspective, it is encouraging to see that president Obama announced $30 M in funding for natural gas vehicles breakthroughs in February 2012 (Department of Energy, 2012). Developing LNG normal temperature storage capability or increasing the safe compression of CNG in order to provide a longer range could be the breakthroughs. With successful implementations of effective precautions and developments, the nation could develop its energy security while it could decrease energy related environmental impact. Individuals could save money by using a cheaper fuel if the life cycle ownership costs of CNG vehicles are not seriously higher than their current vehicles.

What are the possible and most feasible incremental changes (infrastructure, policy, or technology) that would make CNG more available or more cost effective for the US transportation sector?

It is not a secret that vehicle users would not switch their vehicles to CNG unless they anticipate monetary benefit. Even if the structure is well developed and natural gas vehicles provide the highest ranges as a result of their technology, they will still need to be incentivized. This fact is both current for vehicle owners and companies. Thus, effective policies supporting the use of CNG as a transportation fuel would yield the highest impact on availability and cost effectiveness of CNG for the U.S. transportation sector.

What is the best 'short-term scenario' for CNG use in the US transportation sector? What is the best 'long-term scenario' for CNG use in the US transportation sector?

According to the results of our application of analytic hierarchy process based on energy security and environmental impact criteria;

For the short-term:

The best scenario is the utilization of CNG for residential vehicles when increased energy independency has at least strong importance compared to positive environmental impact. CNG usage for cargo and public transportation purposes is the best scenario when the energy security is assessed as moderately, equally, or less important than environmental concern.

For the long-term:

The best scenario is using CNG for cargo and public transportation purposes when energy security is evaluated more important than or equally important as environmental concerns. If energy security is perceived as less important, application of CNG use by the vehicles with no fuel storage space limitation becomes the best scenario. In the next section conclusions inferred from addressing research sub-questions will be provided.

Conclusions

The results of this study on the feasibility of compressed natural gas as a replacement fuel for the U.S. transportation sector, in the light of the information summarized in the previous section, are strongly positive. We have shown evidence that domestic natural gas reserves are promising for a long utilization timeframe, even if the entire energy requirement of transportation sector is met by it. If the limitations regarding refueling and vehicle range can be solved (government subsidies and incentives could aid this), the unutilized natural gas supply infrastructure could meet about half of the total transportation fuel need with very limited additional investments. Resolving these problems should not be considered one of the more difficult undertakings. We exemplified that the federal government could be seen on the right track. In last three years, president Obama and the government announced The Energy Security Act with new fuel efficiency and emission standards. In order to accomplish these bold goals they shook hands with major automakers and shared their vision. Natural gas, as we observed in our target achievement calculations, could be a great tool for reaching these targets. In parallel to the inference of our study, to attract attention to the importance of the issue, president Obama announced $30 M in funding for natural gas vehicle research. The purpose is to encourage scientists, engineers, and entrepreneurs to find ways to harness the abundant supplies of domestic natural gas for vehicles.

Pipeline capacity has increased by 25% in the last four years, even though it was capable of meeting three times the highest daily demand four years ago. Natural gas production capacity, being the bottleneck of natural gas supply system is keeping pace with other system developments. In just 2011, fractioning capacity has increased by 14.7%. Besides the useful conclusions drawn from the application of the analytic hierarchy process to select short-term and long-term scenarios, target achievement values of scenarios has shown that CNG's contribution could be very significant for the success of the federal governments goals.

The feasibility of compressed natural gas as a replacement fuel for the U.S. transportation sector is supported by the robust characteristics of the supply system and CNG itself. The results of this study and the strong initiatives put forth by decision makers, automakers, and infrastructure investors also show support for the extended use of CNG in transportation. In the next section recommendations for further research will be proposed.

Recommendations

Since CNG is proposed as a feasible replacement fuel for the U.S. transportation sector, further research areas reveal themselves intrinsically. Further research could be conducted through investigating the development of natural gas extraction processes to be able to recover a higher rate of the reserves from the reservoirs. Also increasing natural gas processing facility efficiencies to gain an overall processing capacity improvement might be of interest. Natural gas on-board storage capacity and fast home refueling technology developments could be sought. Additional storage options other than underground storage capacity may be inquired.

Recovery capabilities of natural gas captured in hydrate formations could be questioned in order to increase the recoverable reserves. The next topic to study as a result of the development and implementation of natural gas recovery from these reservoirs, if it could be possible, and since the reserves captured in hydrate formations are projected to be much more than underground reserves, could be on the market for export options.

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14. ABSTRACT
There has been much attention for many years on reducing U.S. fuel imports problem in order to improve energy independence. The transportation sector is one of the most important components with its share of 28% of total U.S. energy consumption. In this research, compressed natural gas (CNG) is examined to see if it can provide at least a partial solution to the problem of finding an alternative fuel for the U.S. transportation sector. To be able to answer this question it is essential to understand both the supply and demand sides of the problem. This research aims to exhibit the availability and adequacy of CNG to be a full or partial fuel replacement for U.S. transportation sector needs, the factors that prevent CNG from being a widely used transportation fuel, the cost-benefit of using CNG as a vehicle fuel and feasible changes to make CNG more cost effective. In conjunction with putting forth this information for consideration, the short and long term best scenarios for CNG use in the transportation sector, provided through the application of Analytic Hierarchy Process (AHP), is proposed.

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